# MODULAR MANUFACTURING SIMULATOR
## Users Manual

Distributed by:

## NASA Southeast Alliance for Technology Transfer

Prepared by:

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## Huntsville, AL 35899

Contract:

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## January 1997

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# TECHNOLOGY TWICE USED

Since the agency was established in 1958, a key part of the National Aeronautics and Space Administration's mission has been to make technologies available to American industry so it can be more widely used by the citizens who paid for it. While many people might think that "rocket science" has no application to earthly problems, rocket science in fact employs earthly materials, processes, and designs adapted for space, and which can be adapted for other purposes on Earth.

Marshall Space Flight Center's Technology Transfer Office has outreach programs designed to connect American business, industries, educational institutions, and individuals who have needs, with NASA people and laboratories who may have the solutions. MSFC's national goal is to enhance America's competitiveness in the world marketplace and ensure that the technological breakthroughs by American laboratories benefit taxpayers and the many industries making up our Nation's industrial base.

Activities may range from simple exchanges of technical data to Space Act Agreements which lead to NASA and industry working closely together to solve a problem. The goal is to ensure that America gains and maintains its proper place of leadership among the world's technologically developed nations. Some of the many technologies transferred from NASA to commercial customers include those associated with:

- Welding and fabrication
- Medical and pharmaceutical uses
- Fuels and coatings
- Structural composites
- Robotics

These activities are aimed to achieve the same goal: slowing, halting, and gradually reversing the erosion of American technological leadership. Legislation such as the National Technology Initiative starts at the top and works down through the national corporate structure, while MSFC's activities start at the grassroots level and work up through the small and medium-sized business which form the bulk of our industrial community.

Technology transfer information is available via the worldwide web from MSFC at *http://www.state.fl.us/stac/*. Or contact:

Susan van Ark
MSFC Technology Transfer Office
Marshall Space Flight Center - AT01
Huntsville, AL 35812

or call

205-544-9295
800-USA-NASA
(fax) 205-544-3151
E-mail: *susan.van.ark@msfc.nasa.gov*

## WHAT IS IN THIS REPORT

The Modular Manufacturing Simulator (MMS) is based on the SSE5 simulator was developed in the early 1990's by the University of Alabama in Huntsville (UAH) (Schroer and Wang, 1992). The SSE5 simulator is described in NASA Tech Brief MFS-26284.

Since 1992, the NASA Marshall Space Flight Center (MSFC) has distributed over 800 copies of the SSE5 simulator to manufacturers throughout the country. A recent survey by MSFC indicated that the simulator has been a major contributor to the economic impact of the MSFC technology transfer program. One manufacturer stated that the SSE5 simulator resulted in a savings of $2M annually.

Many of these manufacturers have requested additional features for the SSE5. Consequently, the following features have been added to the MMS that are not available in the SSE5:

- Runs under Windows.
- Print option for both input parameters and output statistics.
- Operator can be fixed at a station or assigned to a group of stations.
- Operator movement based on time limit, part limit, or work-in-process (WIP) limit at next station.
- The movement options for a moveable operator are:

  - Go to station with largest WIP.
  - Rabbit chase where operator moves in circular sequence between stations.
  - Push/Pull where operator moves back and forth between stations.

### Limits to this Report

The Modular Manufacturing Simulator has been developed for the beginning user of computer simulation. Consequently, the MMS cannot model complex systems that require branching and convergence logic. Once a user becomes more proficient in computer simulation and wants to add more complexity, the user is encouraged to use one of the many available commercial simulation systems.

### What this Report will do for you

This users manual contains the necessary information for installing the MMS on a PC, a description of the various MMS commands, and the solutions to a number of sample problems using the MMS. The corresponding MMS models for these sample problems are included on the disk that accompanies this manual.

### MSFC Technology Transfer Mission

As mandated by the Space Act of 1958, NASA transfers the technology and knowledge gained performing research and development in support of space flight to the private sector, including industry, academia, research organizations, and private entrepreneurs.

## What is Technology Transfer

Technology transfer is the process of moving scientific discoveries and newly developed technologies from a federal government laboratory or agency to the non government industrial community. NASA's Marshall Space Flight Center (MSFC) has developed several programs to support American business, industry, and academia. The goal is to ensure that America maintains it technological leadership.

MSFC's national goal in technology transfer is to enhance America's competitiveness in the world market-place and ensure that technological breakthroughs by American laboratories benefit both taxpayers and the many industries making up our nation's industrial base.

## MSFC Technology Transfer Organization

MSFC is a member of the NASA Southeast Technology Transfer Alliance (See Figure 1). The Alliance is a partnership of the three NASA field centers in the southeast region and NASA's Southeast Regional Technology Transfer Center. The purpose of the Alliance is to promote technology transfer throughout the United States to make American industry stronger.

| NASA Center | Telephone |
| --- | --- |
| Marshall Space Flight Center, Huntsville, AL | (800) 872-6272 |
| Kennedy Space Center, Cape Canaveral, FL | (407) 867-3017 |
| Stennis Space Center, Slidell, MS | (601) 688-1929 |
| Southern Technology Applications Center, Aluchua, FL | (800) 472-6785 (in FL) |

Figure 1. NASA Southeast Technology Transfer Alliance

The Technology Transfer Office at MSFC has broadened its activities in an effort to reach out to American businesses, industries, educational institutions, and individuals. These activities are aimed to achieve the same goal: reversing the erosion of American technological leadership. Legislation such as the National Technology Initiative starts at the top and works down through the national corporate structure. MSFC's activities start at the grassroots level and work up through small and medium-sized businesses which form the bulk of our industrial community.

Representatives from MSFC have been assigned to represent the Center to states within the Southeast Alliance for Technology Transfer. MSFC representatives are assigned to the following states: Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, and Tennessee, as shown in Figure 2. (However, they are available to help where needed.) These representatives hold regular meetings with groups at the city and state level to ease the technology transfer process.
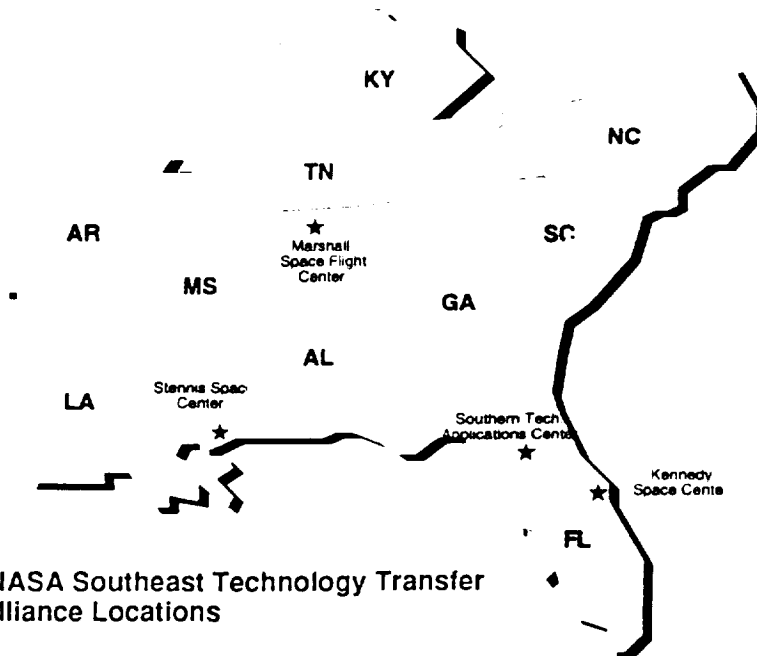
**Figure 2. NASA Southeast Technology Transfer Alliance Locations**

## How can Technology Transfer Help Me

Technology transfer can provide that "missing link" for an industrial process. Sometimes, talking with an expert in a particular field can help businesses make decisions about new processes they would like to try. Academic institutions also benefit by scientific discussions concerning student experiments and questions, and information exchange among academic personnel. The key thing to remember is that these technologies are available for public use.

## What Technologies are Available at MSFC

In order to explore the universe, NASA use the full range of technologies. These are available through patents available for licensing from MSFC. These patents provide advances in welding, bearings, mechanical innovations, air and water pollution control, medical prosthetics, materials fabrication and processes, and many other areas associated with general industry.

Additional information about any of these patents or information about Marshall Space Flight Center's Technology Transfer Program, which features technology assistance to industry through simple, one-page request forms, may be obtained by contacting the MSFC Technology Transfer Office at (205) 544-9295.

## How can I get NASA Technology

There are a number of ways in which the actual transfer may take place, coordinated with the Technology Transfer Office at MSFC. You may initiate access to the available technologies:

- By calling the MSFC Technology Transfer Office, (205) 544-9295 or 800-USA-NASA
- By fax to the MSFC Technology Transfer Office, (205) 544-3151
- By e-mail to: *susan.van.ark@msfc.nasa.gov*
- By using the Technology Transfer Agreement form at the MSFC Technology Transfer World Web site accessed at *http://tectran.msfc.nasa.gov/*

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## DISCRETE EVENT SIMULATION (Schroer, 1992)

A number of tools are available to assist manufacturers in the design, layout, and evaluation of manufacturing lines. One of the more commonly used tools is computer simulation. There are a number of reasons for using simulation. Simulation offers management the ability to evaluate a manufacturing line, or an alternative to a line, before actually installing the line. With simulation the line can be studied under a controlled environment by varying one parameter at a time. In other words, simulation can be considered as inexpensive insurance against costly mistakes.

There are several drawbacks to using computer simulation. One of the most serious is the length of time to develop, verify, and validate the simulation model. Quite often management cannot wait this length of time for the simulation results. A second drawback is that the firm needs someone trained in simulation. This person is not only difficult to locate, but generally cannot be justified on a full-time basis.

### What is Computer Simulation

Simulation consists of developing a representation, or model, of a real-world system and then experimenting with the model to study the operation of the system over time. Models of very simple systems often can be solved mathematically. However, most models of complex, real-world systems cannot, and instead must be solved using simulation. In these instances, a computer model of the system is developed. The computer model is generally written or programmed using commercially available simulation software. With simulation it is possible to manipulate the model rather than the real-world system. In a manufacturing environment, such real-world manipulation is often too expensive and impractical, opening opportunity for the use of simulation.

Figure 3 outlines the steps in a computer simulation. First the user must define the system, or problem. Quite often this step is the most difficult; however, it is the most beneficial to management. Next the user develops a model of the manufacturing system. During the second step the user begins collecting the necessary data for the model.

The third step is the development of the computer simulation model of the manufacturing process. The simulation model is generally written using commercially available simulation software.

The fourth step is to verify that the simulation model, or code, is correct. A number of techniques exist for verifying code, such as running the model with no distributions, running only one transaction through the model and testing each logic branch separately.

The fifth step is to validate that the model does in fact accurately represent the real-world problem. For example, the model outputs, such as daily production, work-in-process and operator utilization, are compared with the actual system. The last step is experimentation with the model. Here, various system alternatives can be simulated and compared to the baseline run.

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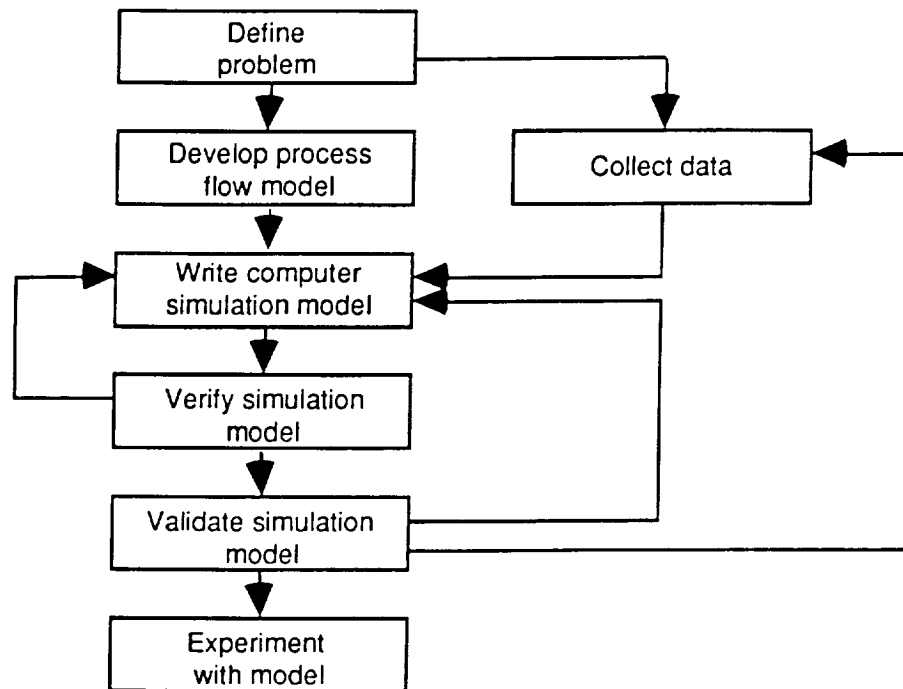
**Figure 3. Simulation modeling process**

## Critical Simulation Issues

"A little knowledge is dangerous" is a true statement in simulation. Computer simulation, while offering rapid evaluation of manufacturing alternatives, generate reams of output. Without a thorough understanding of a simulation model's operation and its limitations, the user may draw erroneous conclusions or receive invalid results from the model. Several critical simulation issues requiring observation by the user are model verification and validation, starting and stopping conditions, and output analysis

**Model Verification and Validation.** One of the most important and difficult tasks in simulation is the verification and validation of the simulation model. Commonly addressed questions during verification are:

- Is the model represented correctly in the simulation code?

- Are the input parameters and logic structure of the model correctly represented in the simulation code?

Commonly used model verification methods are:

- Using the trace feature in the simulation software to trace a transaction through each model segment.

- Turning on the built-in animation features, which are valuable in observing abnormalities during model execution, such as large work-in-process buildup; resources, such as machines and operators not being utilized; and transactions moving through various model segments.

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- Running a single transaction through the model and observing its path, computing the time the transaction was in the system, and then comparing the results with the real world data.

Model validation consists of determining if the model is an accurate representation of the real world system. Validation is usually achieved through an interactive process of comparing the model's behavior to the actual system's behavior. Typical, the validation process consists of a series of discussions between the plant manager, manufacturing engineer and the model developer. The results of each discussion provides greater insight into the actual operation of the system, a sharper definition of the system's operational characteristics and a model that closely represents the actual system. Commonly used model validation methods are:

- Remove all model variation, replace with mean values, run a transaction through the model, and compare transaction time in the system with actual data

- Meet with plant manager and manufacturing engineer and run the model with the animation features on. Often plant personnel notice abnormalities in the model execution not apparent to the modeler.

**Starting and Stopping Conditions.** Two approaches used in starting a simulation model are start the system empty and idle and set the starting conditions as close to steady state mean or mode as possible. The first approach is most commonly used in manufacturing systems because of it simplicity. Using this method, all queues, or buffers, start empty and facilities, or machines, start idle.

A simulation can be terminated by stopping the creation of new events and then allowing the system to return to an empty and idle state. It is important to note that including the measurements collected after terminating new events also introduces bias which can be serious, especially if the total run time is short.

Two approaches commonly used in manufacturing models to determine stopping conditions are to stop the system after a given amount of production or after a given time. By using either of these approaches, no limit is placed on the number of parts entering the system. Therefore, at the completion of the simulation, parts are still in the system and machines are still be utilized.

**Steady State Analysis.** Generally there is no single point during the execution of the simulation model beyond which the system is in steady state, or equilibrium. Therefore, there is a problem in finding the point which the modeler is willing to neglect the error made by considering the system in equilibrium.

One common approach in determining equilibrium is to execute the model for a long enough period of time to ensure the system's performance does not depend on the starting condition of the model. However, in most situations, the error resulting from the initial conditions must be taken into consideration. Several heuristic rules to estimate system steady state are Conway rule; modified Conway rule, crossing of the mean rule, cumulative mean rule and deletion rule.

For example, Figure 4 is a plot of ten batch means with each batch having a sample size of twenty-five observations. These batches are obtained by running the simulation model for a time period sufficient to complete twenty-five parts for each

batch. The response variable, such as production per hour, is then measured. The model continues to run and the response variable is measured after each batch of twenty-five parts. Applying the Conway rule, the fifth batch mean is neither the maximum nor the minimum of the remaining means. Therefore, it is assumed that the system requires four batches, or 100 observations, to reach steady state.
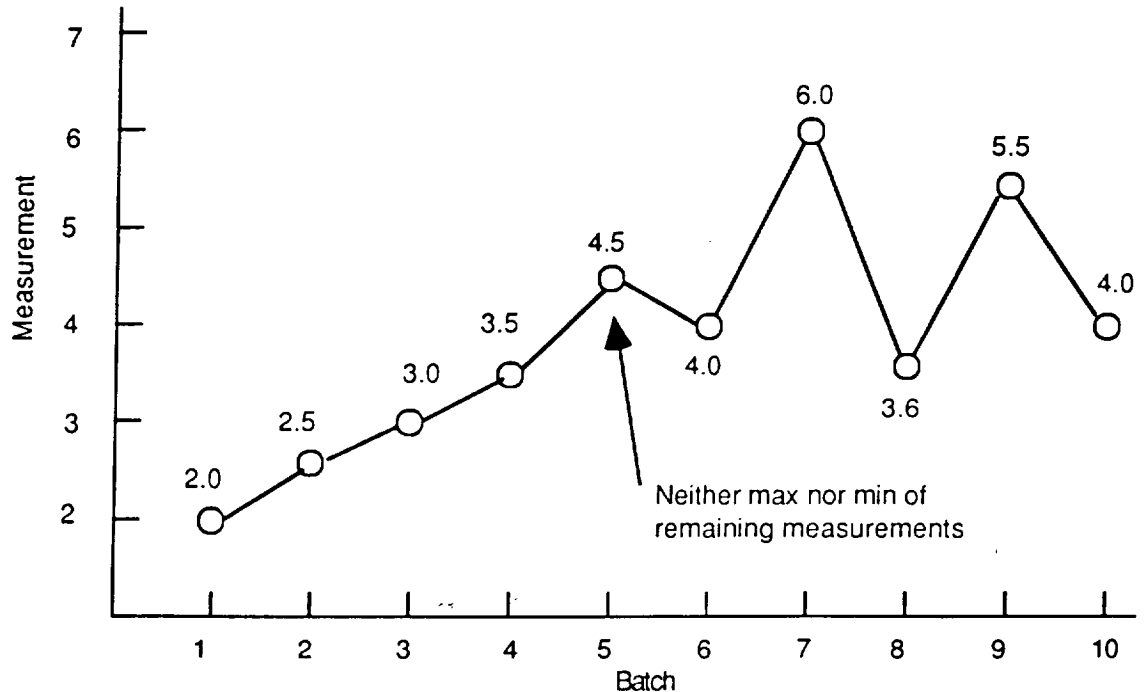


Figure 4. Example of Conway Rule for determining equilibrium

**Output Analysis.** There are several commonly used techniques to analyze the output from a simulation. The fist run of the simulation model is to validate that the model approximates the real world system as closely as possible. This run is often called the baseline run and gives output statistics such as machine utilization, work-in-process (WIP) in front of the various stations, production, production per operator and the time a part is in the system.

These baseline statistics often identify potential abnormalities or problems in the system. For example, at the end of the simulation, if the WIP in front of a station is also the maximum WIP during the simulation, then the system is probably unstable. That is, the queue length is continually increasing and is approaching an infinite queue. As a result, other parameters will also continually increase, such as the time in the system or the time to product a part. The baseline statistics can also identify low operator and machine utilization, excessive WIP, low daily production and system bottlenecks.

An analysis of the statistics from the baseline run should result in the identification of several parameters that could be changed in further simulations runs. One approach in evaluating the effects of these parameters one at a time, and then compare the system's results as a function of this parameter. For example, Figure 5 gives the simulation results for the baseline run of a manufacturing system and four alternative runs. The data suggest that a significant increase in production was

achieved with Alternative A, and a lesser increase was achieved with the other alternatives. Figure 6 gives the corresponding average WIP in the system. Alternative A produces a significant reduction in WIP, while the other alternatives realized lesser WIP reductions.
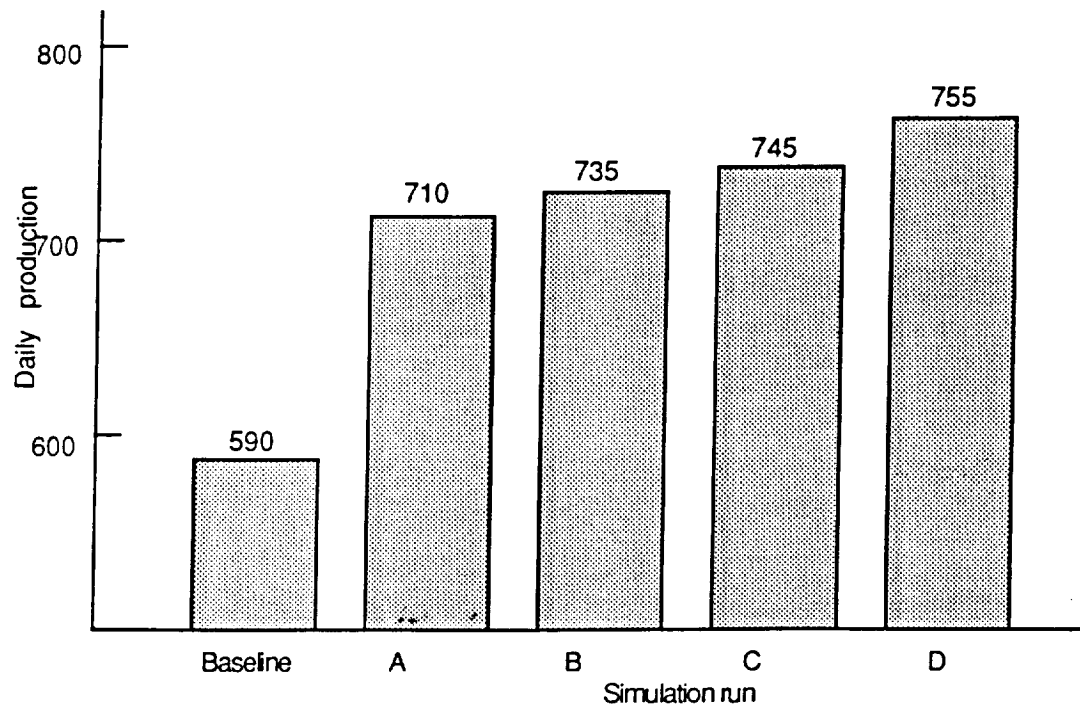


**Figure 5. Production for various simulation runs**
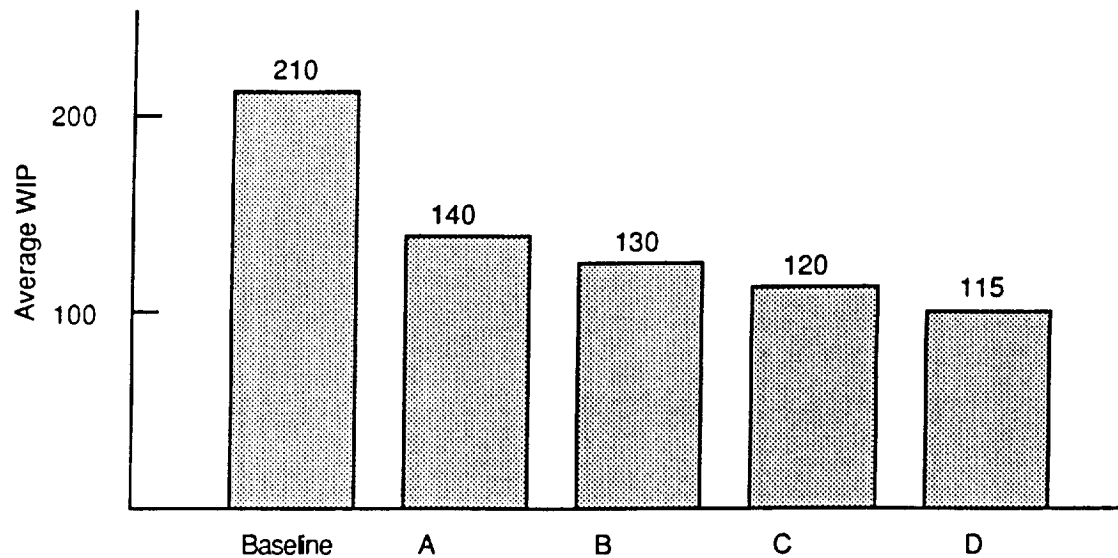


**Figure 6. Average WIP for various simulation runs**

Rather than relying entirely on the absolute simulation output statistics, it is often more advantageous to compare the relative differences between various alternatives. Here the percentage change, either positive or negative, is compared to the baseline run. For example, Figure 7 is a plot of the relative differences in production and WIP as compared with the baseline run. It can be seen that Alternative A increased production 20.3% over the baseline, and Alternative B increased production 24.6% over the baseline. On the other hand, Alternative A decreased WIP 33.3% and Alternative B decreased WIP 38.1%. Alternatives C and D also show an increase in production and a decrease in WIP; however, these changes are not as great relatively when compared to Alternative B.
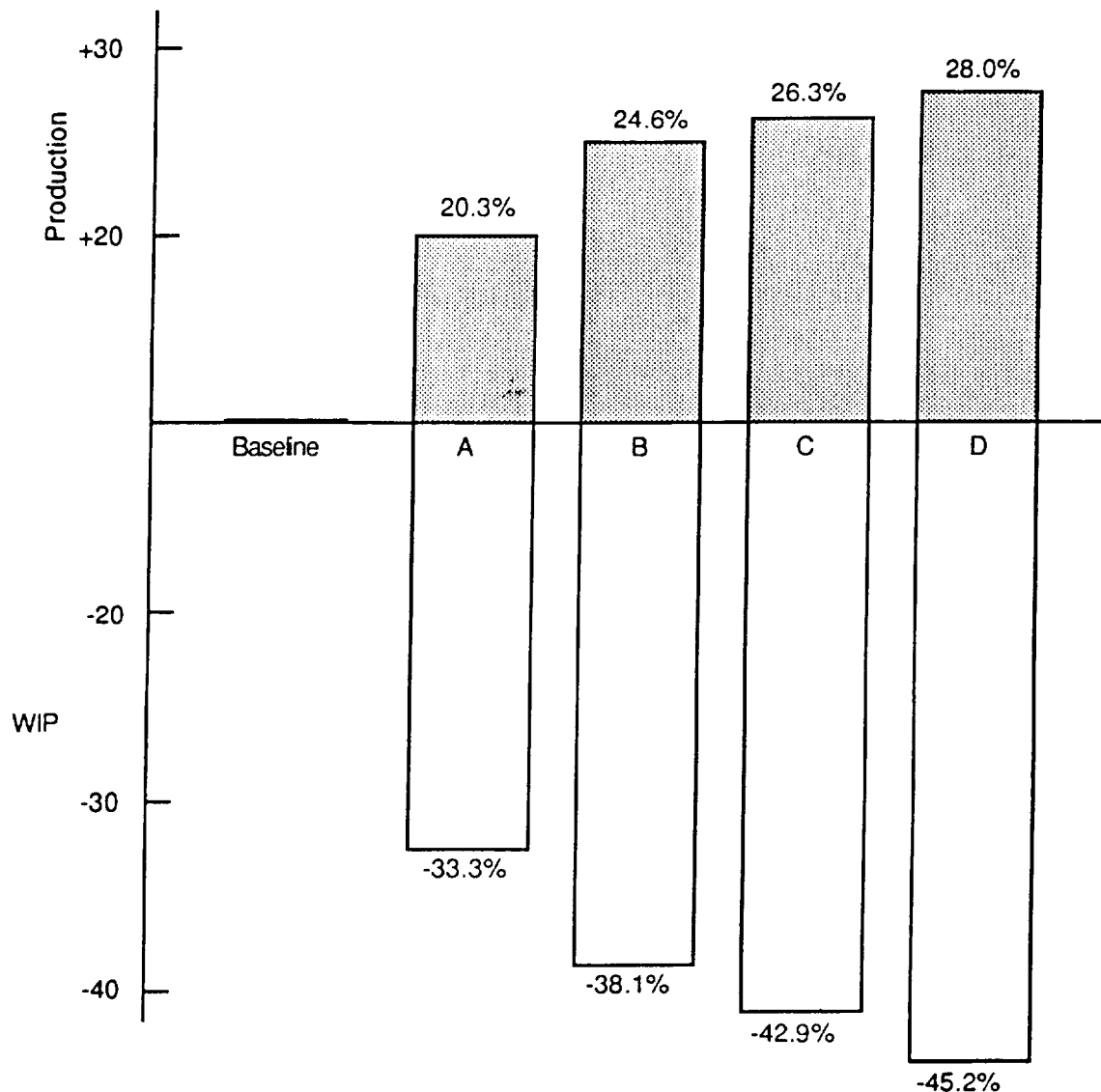


Figure 7. Percent change in production and WIP

Machine or operator utilization and production rates are two standard simulation statistics. The question with regard to these results is "What confidence do we have in these simulation results?" In other words, what is the confidence interval for machine utilization and production rate?

Additional accuracy can be achieved by increasing the run length of the simulation model. For example, doubling the accuracy requires quadrupling the sample size. An often overlooked question is how large of a sample is needed to have some level of confidence in the simulation results. For instance, assume you intend to estimate the average daily production to plus or minus five parts per day with a 95% level of confidence. How large of a sample is needed to satisfy this requirement? Standard statistical techniques can provide the answers to these questions (Banks, et.al., 1996).

## COMMERCIAL SIMULATION SYSTEMS

Several books on discrete event simulation are listed in the bibliography. A complete list of commercially available simulation systems is given in:

"Simulation Survey: Tools for Process Understanding and Improvement," James J. Swain, *OR/MS Today,* August 1995, pages 61-79.

Several commercial manufacturing simulators are:

- Arena

  Systems Modeling Corporation
  504 Beaver St.
  Sewickley, PA 15143
  (412)741-3727

- ProModel

  ProModel Corp
  1987 S. State Street. 3400
  Orem, UT 84058
  (801) 226-4600

- Simfactory II.5

  CACI Products Co.
  3333 N. Torrey Pines Ct.
  La Jolla, CA 92037
  (619)457-9681

- Witness

  AT&T Istel Visual, Inc.
  25800 Science Park Dr.
  Cleveland, OH 44122
  (216)292-2668

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## MODULAR MANUFACTURING SIMULATOR

### Installation

The minimum requirements for installing the Modular Manufacturing Simulator on a PC are:

- Windows 3.1, Windows 95, or Windows NT 4.0
- 386 PC with Mb of memory
- Hard drive

The steps to install the MMS are:

1.   Place MMS disk in disk drive (generally drive A).

2.   Double click on "Setup Icon" which will automatically install the MMS and create an icon in Windows.

3.   To execute the MMS software, return to Windows and click the MMS icon.

4.   Figure 8 is the introductory screen for the MMS.

The MMS is written using Borland C version 3.0.

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**Modular Manufacturing Simulator**


**A  tool for rapidly designing, analyzing,
and visualizing manufacturing modules**

**Distributed by:**

**NASA Southeast Alliance for Technology Transfer**


**Developed by:**

**University of Alabama in Huntsville
Huntsville, AL**


**Copyright 1997
University of Alabama in Huntsville**

**OK**

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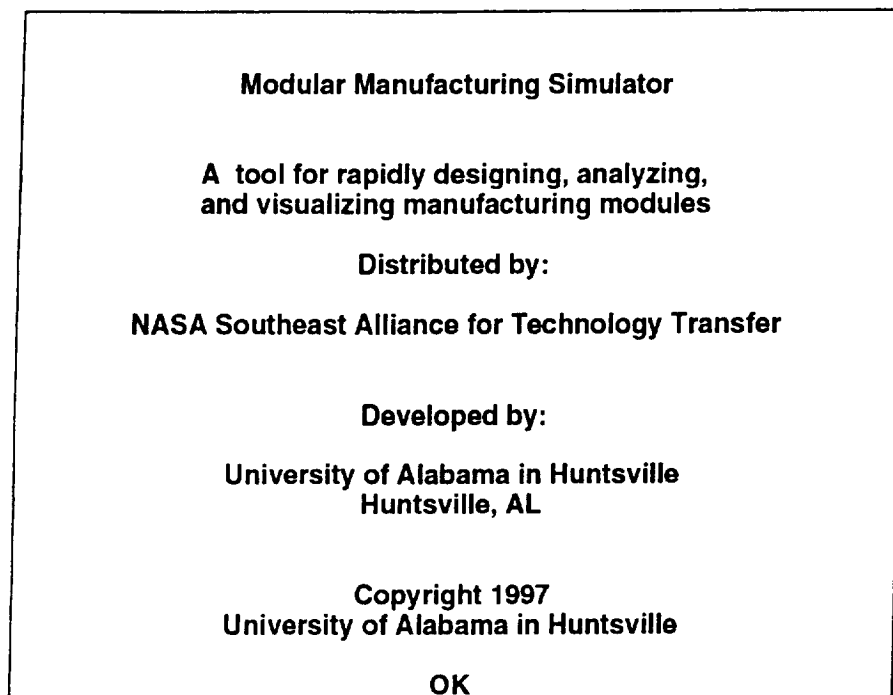
**Figure 8.  MMS introduction screen**

## System Description

The Modular Manufacturing Simulator can be used for designing and analyzing modular manufacturing lines with the following characteristics:

- One line with unlimited number of stations (all stations are in series).
- Each station may have unlimited number of machines with each machine performing the identical operation.
- Unlimited number of operators.
- Unlimited space for WIP in front of each station.
- Always enough WIP in front of the first station so there is no delay waiting for parts.
- Some operators may be fixed at specific stations.
- Some operators may move between a given number of stations.
- The movement of operators is defined by a set of rules.
- Work is done in lots of one part. However, it is possible to perform work in lots of more than one part by defining all values in terms of lots.
- No machine breakdown.

## Model Inputs

The following inputs are necessary for the MMS to construct a model:

- Number of stations.
- Number of machines at each station.
- Number of operators.
- Cycle time distribution at each station (constant, exponential, log normal, normal, triangular, or uniform).

The input parameters for a fixed operator are:

- Priority = 1. The operator is assigned to only one station.
- Operator efficiency = %.

The input parameters for a moveable operator are:

- Operator type = Max WIP, Rabbit Chase, or Push/Pull.
- Priority = 1, 2, 3, ... This is the sequence the operator will move between stations (home station = 1).
- Operator efficiency = %.
- Part limit that the operator makes at this station. Once this limit has been exceeded, the operator tries to move to another station in the priority list (value of 0 to ignore part limit).
- Time limit that operator spends at this station doing work. Idle time is not included in calculating time limit. Once this limit has been exceeded, the operator tries to move to another station in the priority list (value of 0 to ignore time limit).
- WIP limit in front of the next station in manufacturing line (this is not necessarily the next station in the priority list). Once this limit has been exceeded, the operator tries to move to another station in the priority list (value of 0 to ignore WIP limit).
- Override limit = Yes (value of 1) or No (value of 0).

  - Override limit = Y. When part limit, time limit, or WIP limit has not been satisfied and WIP in front of current station is zero, the operator will move to the next station in the priority list. If there is no WIP at any station in the priority list, the operator will stay at current station and be idle.

- Override limit = N. When part limit, time limit or WIP limit has not been satisfied and WIP in front of current station is zero, the operator will stay at current station and be idle.

It should be noted that:

- The WIP limit implies that the operator at Station "i" is producing parts at a faster rate than the operator at Station "i+1" or there is no operator at Station "i+1" and WIP is building in front of this station. When the WIP in front of Station "i+1" exceeds the WIP limit, the operator at Station "i" tries to move to the next station in the priority list.

- If the time limit, part limit, and WIP limit are all set to 0, then the moveable operator will try to move after completing a part.

- If the time limit, part limit or WIP limit is set to 0, then that limit is excluded from consideration. For example, if time limit = 50, part limit = 0, and WIP limit = 0, then the operator will try to move when the time limit of 50 has been exceeded. If time limit = 50, part limit = 20 and WIP = 0, then the operator will try to move when either the time limit or part limit has been exceeded.

- The part limit could easily represent a lot of parts. Then all the cycle times in the model would represent the time to complete a lot of parts rather than one part. In this instance, all the input data must represent the same lot size.

## Operator Movement Rules

The Max WIP Rule is as follows:

- If the operator has worked for more than the time limit or has exceeded the part limit at the current station, or the WIP at the next station has exceeded the WIP limit, the operator will move to the station in the priority list with the largest WIP.

  - If the maximum WIP is at the current station, the operator will stay at the current station and do another part.

  - If the station with the maximum WIP is busy, the operator will move to the station in the priority list with the second largest WIP.

  - If two stations have the same WIP, the operator will move to the station with the higher priority.

  - If all stations are busy, or there is no WIP at any station in the priority list, the operator will stay at the current station and make another part.

The Rabbit Chase Rule is as follows:

- If the operator has worked for more than the time limit or has exceeded the part limit at the current station, or the WIP at the next station has exceeded the WIP limit, the operator will move to the next station in the priority list.

  - If next station is busy or there is no WIP at the station, the operator will skip the station and go to the next station in the priority list.

  - If the operator is at the last station in the priority list, the operator will try to move to the first station in the priority list.

  - If all stations are busy or there is no WIP at any station, the operator will stay at the current station and make another part.

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The Push/Pull Rule is as follows:

- If the operator has worked for more than the time limit or has exceeded the part limit at the current station, or the WIP at the next station has exceeded the WIP limit, the operator will move to the next station in the priority list.

  - If the next station in the priority list is busy or has no WIP at the station, the operator will skip the station and go to the next station in the priority list.

  - If the operator is at the last station in the priority list, the operator will move back one station in the priority list. If this station is busy or has no WIP, the operator will move back two station in the priority list.

A example of each type of moveable operator is given in Figure 9.

## Use of Movement Rules

Let us assume the manufacturing module in Figure 10 and that Operator 3 moves based on the Max WIP Rule. Then:

| | |
|---|---|
| Status: | Operator 3 has been at Station 3 for 30 minutes |
| | WIP at Station 4 = 10 and idle |
| | WIP at Station 5 = 15 and idle |
| Decision: | Operator 3 moves to Station 5 |
| Status: | Operator 3 has been at Station 3 for 30 minutes |
| | WIP at Station 4 = 10 and idle |
| | WIP at Station 5 = 15 and busy |
| Decision: | Operator 3 moves to Station 4 |
| Status: | Operator 3 has been at Station 3 for 30 minutes |
| | WIP at Station 4 = 10 and busy |
| | WIP at Station 5 = 15 and busy |
| Decision: | Operator 3 stays at Station 3 and makes another part |

Let us assume that Operator 3 moves based on the Rabbit Chase Rule. Then:

| | |
|---|---|
| Status: | Operator 3 has been at Station 3 for 30 minutes |
| | Stations 4 and 5 idle |
| Decision: | Operator 3 moves to Station 5 |
| Status: | Operator 3 has been at Station 4 for 30 minutes |
| | Stations 5 and 3 idle |
| Decision: | Operator 3 moves to Station 3 |
| Status: | Operator 3 has been at Station 5 for 30 minutes |
| | Stations 3 and 4 idle |
| Decision: | Operator 3 moves to Station 4 |
| Status: | Operator 3 has been at Station 3 for 30 minutes |
| | Station 4 idle and Station 5 busy |
| Decision: | Operator 3 moves to Station 5 |
| Status: | Operator 3 has been at Station 3 for 30 minutes |
| | Stations 4 and 5 busy |
| Decision: | Operator 3 stays at Station 3 and makes another part |
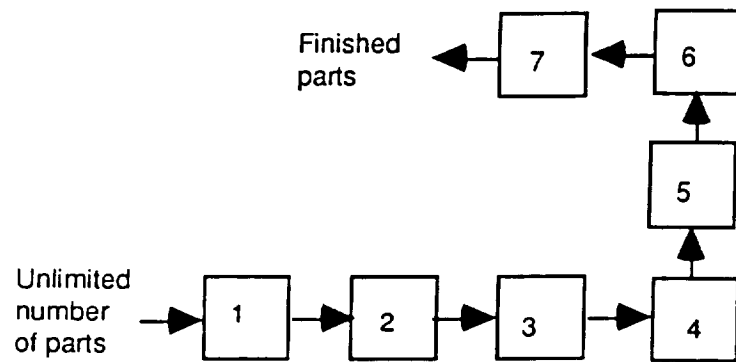
Operator 3 moves between Stations 3, 4 and 5
Priority sequence: 1 = Station 3 (home), 2 = Station 4, and 3 = Station 5.

Operator movement
for Max WIP Rule
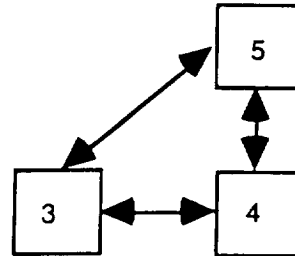
Operator movement
for Rabbit Chase Rule
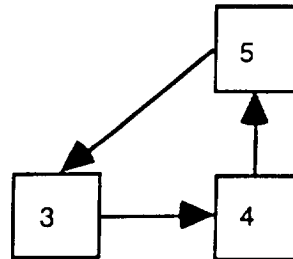
Operator movement
for Push/Pull Rule
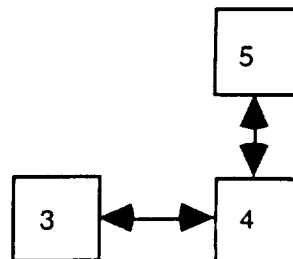
Figure 9.  Example of operator movement rules
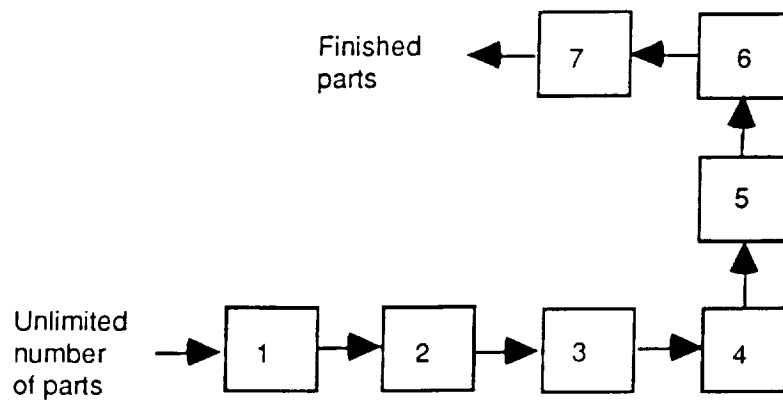
| Station | Number of machines | Cycle time (minutes) |
|---------|--------------------|----------------------|
| 1 | 1 | N(10,2) |
| 2 | 1 | N(8,3) |
| 3 | 1 | N(3,1) |
| 4 | 1 | N(4,1) |
| 5 | 1 | N(3,1) |
| 6 | 1 | N(10,3) |
| 7 | 1 | N(8,2) |

| Operator | Type | Assignment | Efficiency |
|----------|------|------------|------------|
| 1 | Fixed | 1 | 100 |
| 2 | Fixed | 2 | 100 |
| 3 | Moveable | 3(home),4,5 | 3=100, 4=90, 5=90 |
| 4 | Fixed | 6 | 100 |
| 5 | Fixed | 7 | 100 |

For moveable Operator 3

| Station | Priority | Time Limit | Part Limit | Next station WIP limit | Override limit |
|---------|----------|------------|------------|------------------------|----------------|
| 3 | 1(home) | 30 | 100 | 50 | No (value = 0) |
| 4 | 2 | 30 | 100 | 50 | No |
| 5 | 3 | 30 | 100 | 50 | No |

Figure 10. Manufacturing module

Let us assume that Operator 3 moves based on the Push/Pull Rule. Then:

| | |
|---|---|
| Status: | Operator 3 has been at Station 3 for 30 minutes |
| | Stations 4 and 5 idle |
| Decision: | Operator 3 moves to Station 5 |
| | |
| Status: | Operator 3 has been at Station 4 for 30 minutes |
| | Stations 5 and 3 idle |
| Decision: | Operator 3 moves to Station 3 |
| | |
| Status: | Operator 3 has been at Station 5 for 30 minutes |
| | Stations 3 and 4 idle |
| Decision: | Operator moves to Station 4 |
| | |
| Status: | Operator 3 has been at Station 4 for 30 minutes |
| | Station 3 busy and Station 5 idle |
| Decision: | Operator 3 moves to Station 5 |
| | |
| Status: | Operator 3 has been at Station 3 for 30 minutes |
| | Stations 4 and 5 busy |
| Decision: | Operator 3 stays at Station 3 and makes another part. |

## Constraints for Using the MMS

It should be noted that the MMS always assumes WIP in front of Station 1. However, it is possible to use a dummy operator to control the entry of parts into the module. For example, let us assume the work day consists of eight hours, or 480 minutes less 20 minutes for breaks, for a total of 460 minutes. Also, let us assume that we would like a daily production of 230 parts from the module.

We can assign a dummy operator to Station 1 with a cycle time of:

$$460 \text{ minutes/1 day} \cdot 1 \text{ day/230 garments} = 460/230 = 2 \text{ minutes/part.}$$

Operator 1, the fixed dummy operator, will complete an operation every two minutes. A part will then arrive at Station 2 every two minutes. With this constraint, the maximum daily production (in 460 minutes) will be 230 parts (provided that the cycle time at each of the other stations is two minutes or less and there are a sufficient number of operators). Also, with this arrival rate of a part every two minutes, the MMS statistical outputs will indicate the percentage of idle time for each operator which can then be used to optimize operator assignment within the module.

As another example, let us assume an arrival rate of ten parts per minute into the manufacturing module. This is equivalent of a part every six seconds. We can assign a fixed operator to a dummy Station 1 with a cycle time of six seconds. Therefore, a part would arrive at Station 2, or the module, every six seconds.

## MODULAR MANUFACTURING SIMULATOR EXECUTION

The MMS operates in the Windows environment. Figure 11 outlines the MMS options. Each of these options is discussed in the following sections.

```
         File              Edit            Simulate          Statistics       Help
          |                 |                 |                 |
          ├ New             ├ Cut             ├ Run             ├ Summary
          ├ Open            ├ Copy            ├ Step            ├ Station
          ├ Save            ├ Paste           ├ Continue        ├ Operator
          ├ Save as         ├ Stations        ├ Pause           └ Wip
          ├ Print           └ Operators       ├ Terminate
          ├ Print input                       └ Reset RN
          ├ Print results
          └ Exit
```
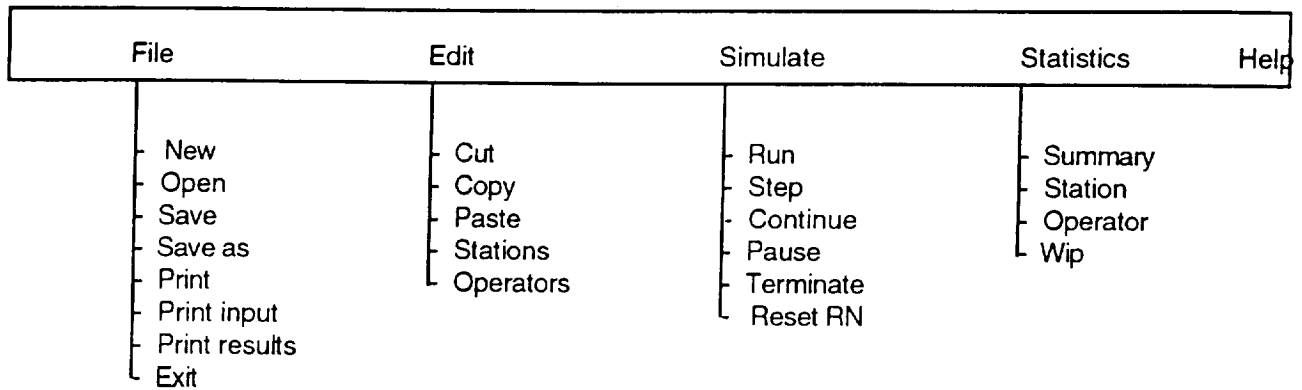
**Figure 11. MMS options**

## File Options

The following file options are available:

| | | |
|---|---|---|
| • | New | Define new model (See Figure 12). Input: |
| | | Number of stations |
| | | Number of operators |
| • | Open | Load previously stored model (See Figure 13). |
| • | Save | Save update to the model (See Figure 13). |
| • | Save as | Save new model. Always save model as name.dat (See Figure 13). |
| • | Print | Print existing screen, or screen dump. |
| • | Print input | Print description of input model. |
| • | Print results | Print simulation statistics. |
| • | Exit | Exit MMS. |

## Edit Options

The following options are available:

| | | |
|---|---|---|
| • | Cut | Not used. |
| • | Copy | Not used. |
| • | Paste | Not used. |
| • | Stations | Input or edit the following (See Figure 14): |

Distribution parameters depend on selected distribution. The parameters are:
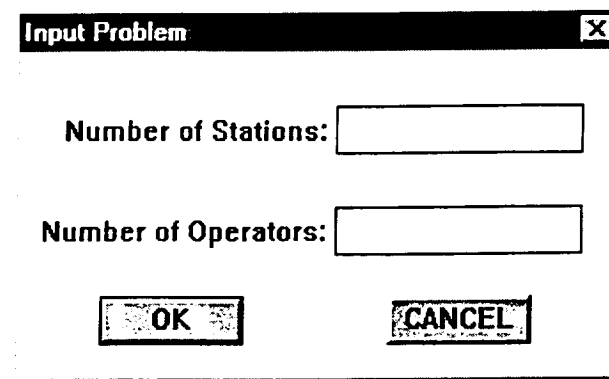
| | |
|---|---|
| Constant | Parameter1 = value |
| Exponential | Parameter1 = mean |
| Log normal | Parameter1 = mean, Parameter2 = standard deviation |
| Normal | Paramter1 = mean, Parameter2 = standard deviation |
| Triangular | Parameter1 = minimum, Parameter2 = middle, Parameter3 = maximum |

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**Figure 12. Define new model**



**Figure 13. Open or save model**

| Name | Machines | Time Dist | Parameter 1 | Paramater 2 | Parameter 3 |
|------|----------|-----------|-------------|-------------|-------------|
| Sta-1 | 1 | Constant | 10.0 | 0.00 | 0.00 |
| Sta-2 | 1 | Constant | 20.0 | 0.00 | 0.00 |
| Sta-3 | 1 | Constant | 40.0 | 0.00 | 0.00 |
| Sta-4 | 1 | Constant | 20.0 | 0.00 | 0.00 |

**Figure 14. Station input**

| | Operator 1 | Operator 2 |
|---|-----------|-----------|
| Name<br>Type | Operator-1<br>PUSH/PULL | Operator-2<br>PUSH/PULL |
| Sta-1 | 1,100,0,0,0,0 | 1,100,0,0,0,0 |
| Sta-2 | 2,100,0,0,0,0 | 2,100,0,0,0,0 |
| Sta-3 | 3,100,0,0,0,0 | 3,100,0,0,0,0 |
| Sta-4 | 4,100,0,0,0,0 | 4,100,0,0,0,0 |

**Figure 15. Operator movement input**

<div align="center">Uniform           Parameter1 = minimum, Parameter2 = maximum</div>

- Operators      Input or edit the following (See Figure 15):

  Operator name
  Operator type (fixed, move based on MAX WIP Rule, move based on Push/Pull Rule, or move based on Rabbit Chase Rule)
  Priority (1 for fixed operator, 1,2,3,... for other types)
  Operator efficiency (%)
  Part limit
  Time limit
  Next station WIP limit
  Override limit (1 = yes, 0 = no) (default = 0)

## Simulation Options

The following options are available:

- Run      Before executing the model, define:

  Run length for the model
  Time for model to reach steady state
  Simulation speed. 0 is fastest. 9 is used with the Step option to step through the model during debugging
  Select random number generator (1-9). The MMS has nine random number generators. The user can select any generator.

- Step      Must first select Pause to stop simulation. Select Step (F2 key) to manually move the simulation through each change in state.

- Continue      Must first select Pause to stop simulation. This option will resume the simulation.

- Pause      Will stop simulation. Select Continue to resume simulation or Step to manually move through the simulation.

- Terminate      Will terminate simulation.

- Reset RN      Will reset the random number seed.

During the simulation the display in Figure 16 will show the state of the module. Specifically, the display will show the parts moving through the module, the WIP in front of each station, and operator movement between stations.

Note that the user can control the animation by selecting the Pause option and then the Step option to see the movement of parts through the stations. The user must continually select the Step option (F2 key) to move the simulation to the next state. The Continue option will resume the simulation.

## Constraints

It should be noted that the MMS cannot model manufacturing lines:

- Where subassembly lines feed the manufacturing line
- Where the line diverges into two or more lines
- Where two lines converge into one line

<div align="center">21</div>

File Edit Simulation Statistics Help

Time: 2600.00
Simulation time: 2000.00
Parts produced: 20

| Operator | 1 | 2 | 3 | 4 | 5 |
|----------|---|---|---|---|----|
| at station | 1 | 3 | 5 | 7 | 12 |

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|
| Sta-1 | Sta-2 | Sta-3 | Sta-4 | Sta-5 | Sta-6 | Sta-7 | Sta-8 |

WIP 1  WIP 0  WIP 0  WIP 0  WIP 0  WIP 0  WIP 0  WIP 0
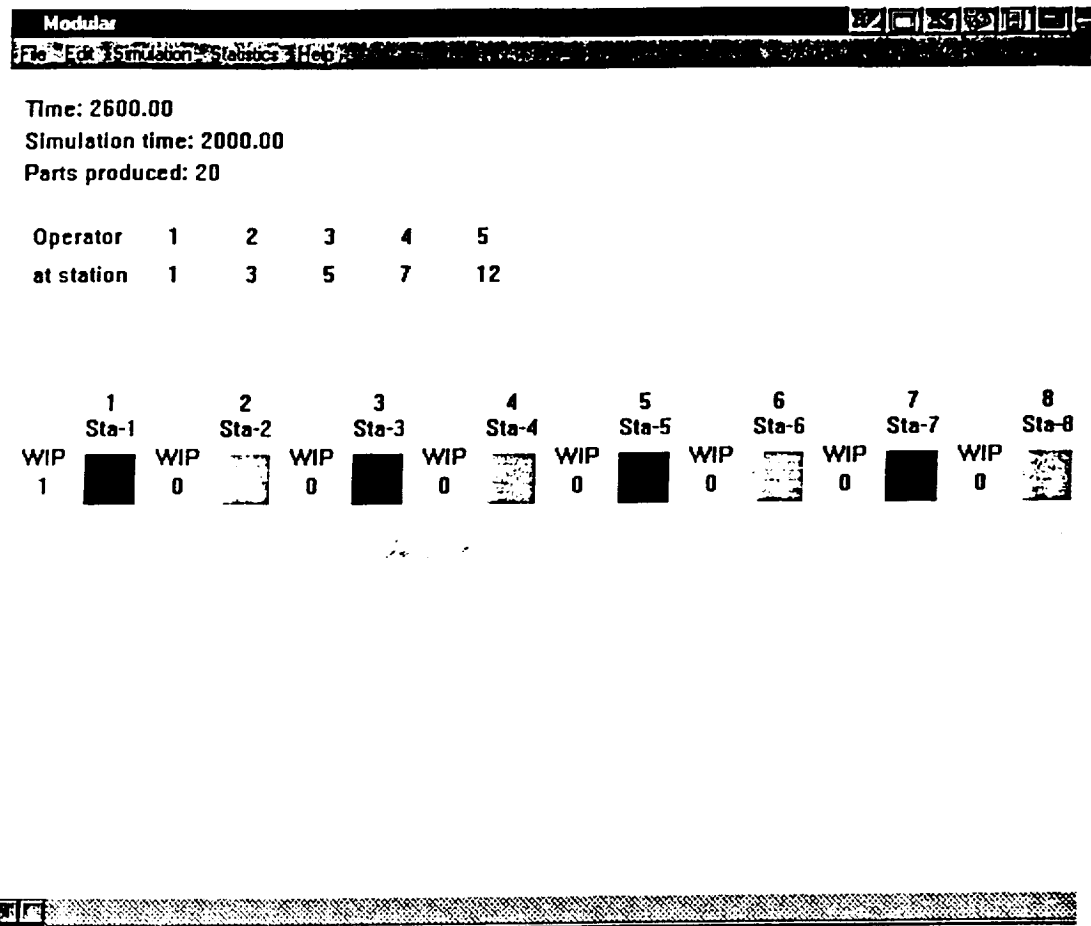
**Figure 16. Animation screen**

## Statistics Options

The following options are available:

- Summary     Displays production results (See Figure 17).
- Stations    Displays machine utilization (See Figure 18).
- Operators   Displays operator utilization by station (See Figure 19).
- WIP         Displays queue statistics by station (See Figure 20).

Note that the user can receive hard copy of these statistics by selecting the Print screen or Print Results under File.

| | |
|---|---|
| Simulation Time | 3600.00 |
| Initialization Time | 300.00 |
| Simulation Start Time | 15:46:33 |
| Simulation End TIme | 15:46:34 |
| Items Produced | 80 |

Figure 17. Parts production results

| Name | WIP | Machines | Busy % | Operations |
|---|---|---|---|---|
| Sta-1 | 1 | 1 | 21.94 | 79 |
| Sta-2 | 0 | 1 | 44.44 | 80 |
| Sta-3 | 0 | 1 | 89.17 | 80 |
| Sta-4 | 0 | 1 | 44.44 | 80 |

Figure 18. Machine utilization

| Station | Avg WIP | Avg Time | In | Out | Now | Min | Max |
|---|---|---|---|---|---|---|---|
| Sta-1 | 1.00 | 45.00 | 80 | 80 | 1 | 1 | 1 |
| Sta-2 | 0.00 | 0.00 | 79 | 79 | 0 | 0 | 1 |
| Sta-3 | 0.09 | 4.12 | 80 | 80 | 0 | 0 | 2 |
| Sta-4 | 0.13 | 5.88 | 80 | 80 | 0 | 0 | 3 |

Figure 19. Queue statistics

| | Operator 1 | Operator 2 |
|---|---|---|
| Idle % | 0.00 | 0.00 |
| Sta-1 | 10.00 | 11.94 |
| Sta-2 | 20.56 | 23.89 |
| Sta-3 | 48.33 | 40.83 |
| Sta-4 | 21.11 | 23.33 |

Figure 20. Operator utilization

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# SAMPLE PROBLEMS

## Problem 1

Figure 21 is a manufacturing module consisting of thirteen stations. Let us assume:

- Operators work at 100% efficiency at all stations.
- Operators will try to move after making one part. Therefore, Time limit, Part limit, and Next station WIP limit are all zeros.
- All operators move following Rabbit Chase Rule.
- Override limit (0 = no)
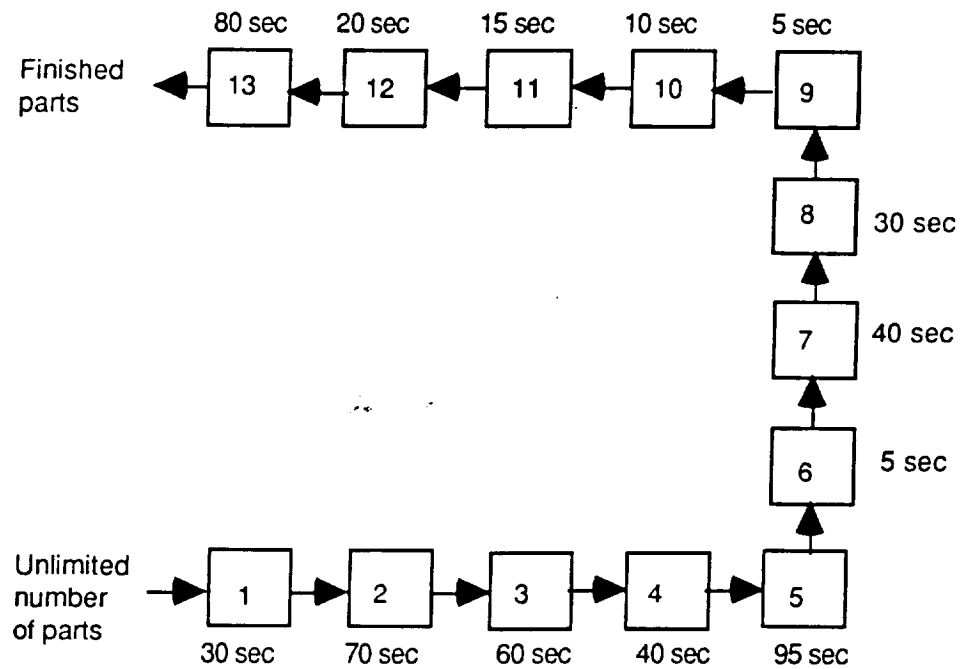


| Operator | Operator station assignment |
|----------|------------------------------|
| 1 | 2 (home, priority = 1), 1 |
| 2 | 4 (home), 3 |
| 3 | 6 (home), 5 |
| 4 | 11 (home), 10, 9, 8, 7 |
| 5 | 13 (home), 12 |

Figure 21. Problem 1

Figure 22 is the display of the station input data. Figure 23 is the display of the operator movement data. Figure 24 contains the MMS model inputs. Figure 25 contains the MMS simulation results. The file name of the model on the disk is *tss1.dat.*

| Name | Machines | Time Dist | Parameter 1 | Parameter 2 | Parameter 3 |
|------|----------|-----------|-------------|-------------|-------------|
| Sta-1 | 1 | Constant | 30.00 | 0.00 | 0.00 |
| Sta-2 | 1 | Constant | 70.00 | 0.00 | 0.00 |
| Sta-3 | 1 | Constant | 60.00 | 0.00 | 0.00 |
| Sta-4 | 1 | Constant | 40.00 | 0.00 | 0.00 |
| Sta-5 | 1 | Constant | 95.00 | 0.00 | 0.00 |
| Sta-6 | 1 | Constant | 5.00 | 0.00 | 0.00 |
| Sta-7 | 1 | Constant | 40.00 | 0.00 | 0.00 |
| Sta-8 | 1 | Constant | 30.00 | 0.00 | 0.00 |
| Sta-9 | 1 | Constant | 5.00 | 0.00 | 0.00 |
| Sta-10 | 1 | Constant | 10.00 | 0.00 | 0.00 |
| Sta-11 | 1 | Constant | 15.00 | 0.00 | 0.00 |
| Sta-12 | 1 | Constant | 20.00 | 0.00 | 0.00 |
| Sta-13 | 1 | Constant | 80.00 | 0.00 | 0.00 |

Figure 22. Station input for Problem 1

| | Operator 1 | Operator 2 | Operator 3 | Operator 4 | Operator 5 |
|------|------------|------------|------------|------------|------------|
| Name Type | Operator-1 RABBIT CHASE | Operator-2 RABBIT CHASE | Operator-3 RABBIT CHASE | Operator-4 RABBIT CHASE | Operator-5 RABBIT CHASE |
| Sta-1 | 2,100,0,0,0,0 | | | | |
| Sta-2 | 1,100,0,0,0,0 | | | | |
| Sta-3 | | 2,100,0,0,0,0 | | | |
| Sta-4 | | 1,100,0,0,0,0 | | | |
| Sta-5 | | | 2,100,0,0,0,0 | | |
| Sta-6 | | | 1,100,0,0,0,0 | | |
| Sta-7 | | | | 5,100,0,0,0,0 | |
| Sta-8 | | | | 4,100,0,0,0,0 | |
| Sta-9 | | | | 3,100,0,0,0,0 | |
| Sta-10 | | | | 2,100,0,0,0,0 | |
| Sta-11 | | | | 1,100,0,0,0,0 | |
| Sta-12 | | | | | 2,100,0,0,0,0 |
| Sta-13 | | | | | 1,100,0,0,0,0 |

Figure 23. Operator movement input for Problem 1

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```
MODULAR MANUFACTURING SIMULATOR

Date: 8/20/1996
Model: A:\TSS1.DAT

MODEL INPUT

Stations: 13
Operators: 5

  Station            Number of  Cycle Time
No. Name              Machines  Distribution
-----------------------------------------------
1   Sta-1               1        Constant(30.000)
2   Sta-2               1        Constant(70.000)
3   Sta-3               1        Constant(60.000)
4   Sta-4               1        Constant(40.000)
5   Sta-5               1        Constant(95.000)
6   Sta-6               1        Constant(5.000)
7   Sta-7               1        Constant(40.000)
8   Sta-8               1        Constant(30.000)
9   Sta-9               1        Constant(5.000)
10  Sta-10              1        Constant(10.000)
11  Sta-11              1        Constant(15.000)
12  Sta-12              1        Constant(20.000)
13  Sta-13              1        Constant(80.000)

OPERATOR ASSIGNMENT

                                            Station Assignment
Operator  Name              Type            No.  Name
-----------------------------------------------------------
1         Operator-1        RABBIT CHASE
2         Operator-2        RABBIT CHASE
3         Operator-3        RABBIT CHASE
4         Operator-4        RABBIT CHASE
5         Operator-5        RABBIT CHASE

OPERATOR MOVEMENT

                                         Part   Time   Next Station  Override
Operator     Station       Prio  Eff    Limit  Limit  WIP Limit     Limit
             No.  Name
------------------------------------------------------------------------------
                                                                        0
Operator-1   1    Sta-1      2    100    0      0      0               0
             2    Sta-2      1    100    0      0      0               0
Operator-2   3    Sta-3      2    100    0      0      0               0
             4    Sta-4      1    100    0      0      0               0
Operator-3   5    Sta-5      2    100    0      0      0               0
             6    Sta-6      1    100    0      0      0               0
Operator-4   7    Sta-7      5    100    0      0      0               0
             8    Sta-8      4    100    0      0      0               0
             9    Sta-9      3    100    0      0      0               0
             10   Sta-10     2    100    0      0      0               0
             11   Sta-11     1    100    0      0      0               0
Operator-5   12   Sta-12     2    100    0      0      0               0
             13   Sta-13     1    100    0      0      0               0
```

Figure 24.  Model Input report for Problem 1

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MODULAR MANUFACTURING SIMULATOR

Date: 8/20/1996
Model: A:\TSS1.DAT

SIMULATION RESULTS

Run length: 21600.00
Initialization length: 500.00
RN generator: 1

Production: 216

MACHINE STATISTICS

| Station No. | Name | WIP | Machine | %Busy | Number of Operations |
|---|---|---|---|---|---|
| 1 | Sta-1 | 1 | 1 | 30.00 | 216 |
| 2 | Sta-2 | 0 | 1 | 70.00 | 216 |
| 3 | Sta-3 | 0 | 1 | 60.00 | 216 |
| 4 | Sta-4 | 0 | 1 | 40.00 | 216 |
| 5 | Sta-5 | 0 | 1 | 95.00 | 216 |
| 6 | Sta-6 | 0 | 1 | 5.00 | 216 |
| 7 | Sta-7 | 0 | 1 | 40.00 | 216 |
| 8 | Sta-8 | 0 | 1 | 30.00 | 216 |
| 9 | Sta-9 | 0 | 1 | 5.00 | 216 |
| 10 | Sta-10 | 0 | 1 | 10.00 | 216 |
| 11 | Sta-11 | 0 | 1 | 15.00 | 216 |
| 12 | Sta-12 | 0 | 1 | 20.00 | 216 |
| 13 | Sta-13 | 0 | 1 | 80.00 | 216 |

BUFFER STATISTICS

| Station No. | Name | Avg WIP | Avg Time | In | Out | Now | Min | Max |
|---|---|---|---|---|---|---|---|---|
| 1 | Sta-1 | 1.00 | 100.00 | 216 | 216 | 1 | 1 | 1 |
| 2 | Sta-2 | 0.00 | 0.00 | 216 | 216 | 0 | 0 | 1 |
| 3 | Sta-3 | 0.00 | 0.00 | 216 | 216 | 0 | 0 | 1 |
| 4 | Sta-4 | 0.00 | 0.00 | 216 | 216 | 0 | 0 | 1 |
| 5 | Sta-5 | 0.00 | 0.00 | 216 | 216 | 0 | 0 | 1 |
| 6 | Sta-6 | 0.00 | 0.00 | 216 | 216 | 0 | 0 | 1 |
| 7 | Sta-7 | 0.00 | 0.00 | 216 | 216 | 0 | 0 | 1 |
| 8 | Sta-8 | 0.00 | 0.00 | 216 | 216 | 0 | 0 | 1 |
| 9 | Sta-9 | 0.00 | 0.00 | 216 | 216 | 0 | 0 | 1 |
| 10 | Sta-10 | 0.00 | 0.00 | 216 | 216 | 0 | 0 | 1 |
| 11 | Sta-11 | 0.00 | 0.00 | 216 | 216 | 0 | 0 | 1 |
| 12 | Sta-12 | 0.00 | 0.00 | 216 | 216 | 0 | 0 | 1 |
| 13 | Sta-13 | 0.00 | 0.00 | 216 | 216 | 0 | 0 | 1 |

OPERATOR UTILIZATION(%) BY STATION

| Station No. | Name | Operator 1 | Operator 2 | Operator 3 | Operator 4 | Operator 5 |
|---|---|---|---|---|---|---|
| Idle | | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1 | Sta-1 | 30.00 | | | | |
| 2 | Sta-2 | 70.00 | | | | |
| 3 | Sta-3 | | 60.00 | | | |
| 4 | Sta-4 | | 40.00 | | | |
| 5 | Sta-5 | | | 95.00 | | |
| 6 | Sta-6 | | | 5.00 | | |
| 7 | Sta-7 | | | | 40.00 | |
| 8 | Sta-8 | | | | 30.00 | |
| 9 | Sta-9 | | | | 5.00 | |
| 10 | Sta-10 | | | | 10.00 | |
| 11 | Sta-11 | | | | 15.00 | |
| 12 | Sta-12 | | | | | 20.00 |
| 13 | Sta-13 | | | | | 80.00 |

Figure 25. Simulation output report for Problem 1

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## Problem 2

Let us change Problem 1 and have all operators move following Push/Pull Rule. Appendix A contains the model input and the simulation results. The file name of the model on the disk is *tss2.dat.*

## Problem 3

Let us change Problem 1 and have parts arrive at the module every 200 seconds. Appendix A contains the model input and the simulation results. The file name of the model on the disk is *tss3.dat.*

## Problem 4

Figure 26 is a layout of a manufacturing line that contains five stations and three operators. The model is run for 3,600 seconds with no warm-up. The file name of the model on the disk is *over1.dat.*

The model was initially run with the override limit left unchecked (value = 0). Appendix B contains the model input and the simulation results. Since the override limit boxes were left unchecked (value = 0), operators only change stations when their defined limits have been exceeded, regardless of whether there is any work at their station. The following can be observed by using the Step function to move through the model execution:

- At time 1,450, Operator 2 becomes idle because there is no work at Station 3. Operator 2 will remain idle until either work becomes available at Station 3 or the time limit of 900 seconds is exceeded.
- At time 1,640, Operator 3 becomes idle at Station 2. Operator 3 will remain idle until either work becomes available at Station 2 or the part limit of 5 parts is exceeded.

Let us make the following changes to the problem:

- Check the override limit boxes (value = 1) for all operators and all stations.
- Reset the random number generator.

The model is run for 3,600 seconds with no warm-up. Random number generator 1 was used in the simulation. Appendix B contains the model input and the simulation results. The file name on the disk is *over2.dat.*

Since the override limit boxes were checked (value = 1), operators will move when either their defined limits have been exceeded or when there is no work at the current station, whichever comes first. The following can be observed by using the Step function to move through the model execution:

- At time 1,450, Operator 2 moves from Station 3 to Station 2 because there is no work at Station 3. This move occurs before the time limit of 900 seconds is exceeded.

- At time 1,510, Operator 2 moves from Station 2 to Station 3 because there is no work at Station 2. This move occurs before the time limit of 900 seconds is exceeded.

- At time 1,590, Operator 2 moves from Station 3 to Station 1 because there is no work at Station 3. This move occurs before the time limit of 900 seconds is exceeded.

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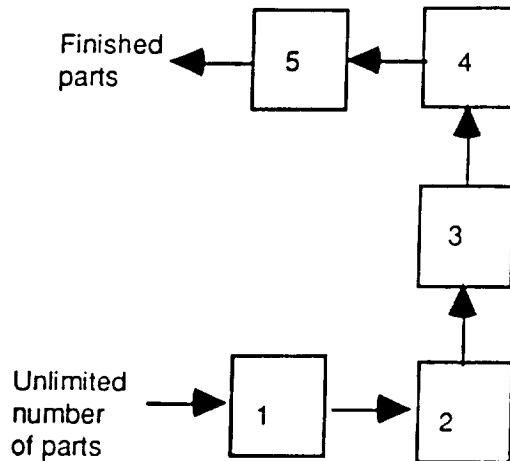
| Station | Number of machines | Cycle time (seconds) |
|---|---|---|
| 1 | 1 | 30 |
| 2 | 1 | 30 |
| 3 | 1 | 40 |
| 4 | 1 | 30 |
| 5 | 1 | 30 |

| Operator | Type | Assignment | Efficiency |
|---|---|---|---|
| 1 | Max WIP | 1 (home),2,3,4,5 | 100 |
| 2 | Max WIP | 3 (home),4,5,1,2 | 100 |
| 3 | Max WIP | 2 (home), 3,4,5,1 | 100 |

| Station | Priority | Time limit | Part limit | Next station WIP limit |
|---|---|---|---|---|
| Operator 1 | | | | |
| 1 | 1 | 0 | 0 | 2 |
| 2 | 2 | 0 | 0 | 2 |
| 3 | 3 | 0 | 0 | 2 |
| 4 | 4 | 0 | 0 | 2 |
| 5 | 5 | 0 | 0 | 2 |
| Operator 2 | | | | |
| 1 | 4 | 900 | 0 | 0 |
| 2 | 5 | 900 | 0 | 0 |
| 3 | 1 | 900 | 0 | 0 |
| 4 | 2 | 900 | 0 | 0 |
| 5 | 3 | 900 | 0 | 0 |
| Operator 3 | | | | |
| 1 | 5 | 0 | 5 | 0 |
| 2 | 1 | 0 | 5 | 0 |
| 3 | 2 | 0 | 5 | 0 |
| 4 | 3 | 0 | 5 | 0 |
| 5 | 4 | 0 | 5 | 0 |

Figure 26. Manufacturing line for Problem 4

The simulation results, when the override limit was NOT used, was 52 units. The simulation results, when using the override limit, was 64 units. This increase in production is because of the decreased/eliminated idle time of the operators when using the override limit.

## CASE STUDY

The layout of a very simple manufacturing line is given in Figure 27. The line receives parts at Station 1 and processes the parts through four stations in series. The characteristics for the line are:

- One machine at each station.
- All work is done in lots of one part.
- Only one operator can work at a machine at a time.
- Once an operator starts a part at a machine, the operator is not interrupted until the part is completed.
- All operators work at 100% efficiency.
- No machine breakdown.
- Always parts in front of Station 1.

Operators can be assigned to specific stations or can move between stations. If an operator is assigned to a specific station, we can consider the machine and the operator the same. On the other hand, if the operator is assigned to several stations, we need to define a set of rules that govern operator movement.
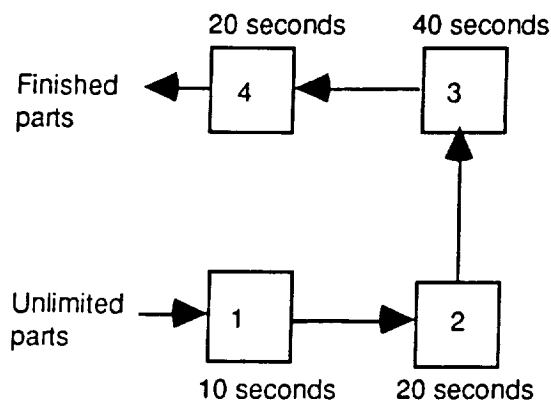


Figure 27. Manufacturing module

## Four Operators

Let us assume that one operator is fixed to each of the four stations. We would like to evaluate the production of the line, operator utilization, station utilization, and work-in-process in front of each station.

The total cycle time for a part through the module is:

10 + 20 + 40 + 20 = 90 seconds.

The average time an operator works on a part is:

90 seconds/4 operators = 22.5 seconds.

Since the maximum cycle time at Station 3 of 40 seconds is greater than the average time per operator of 22.5 seconds, the theoretical hourly production is:

3600 seconds/1 hour • 1 part/40 seconds = 90 parts/hour.

Station utilization is the percent of time the station was in use during the simulation. The operators are fixed at the stations. Therefore, operator utilization will equal station utilization. Since we assumed one part is always in front of Station 1, the utilization of Station 1 is 100%. Likewise, since the cycle time at Station 1 is less than Station 2, the utilization of Station 2 will also be 100%. Since the cycle time at Station 2 is less than Station 3, the utilization of Station 3 will also be 100%. However, since the cycle time at Station 4 is less than Station 3, the utilization of Station 4 will be less than 100%. The ratio of the cycle time of Station 4 to Station 3 is 20/40; therefore, an estimate of the utilization of Station 4 is 50%.

The WIP in the module should continue to increase over time since the line is not balanced with four fixed operators. We would estimate no WIP in front of Station 4 since its utilization is not 100% and since the cycle time at Station 3 is greater than Station 4. We would estimate a large WIP in front of Station 3 and an even larger WIP in front of Station 2 since these cycle times are greater that the cycle time at Station 1.

We do not need a simulation model to evaluate the line when an operator is fixed at each station. However, we will use the Modular Manufacturing Simulator to validate our assumptions. The MMS is run for 300 seconds to reach equilibrium. After reaching equilibrium, the MSS runs for 3,600 seconds, or one hour of simulation time. The model input and simulation results are given in Appendix C. The file name of the model on the disk is **mod4.dat**.

### One Operator

Let us now assume that the line has only one operator who works at all four stations. Let us further assume that the operator will start a part at Station 1 and then move with that part through the remaining stations. After completing a part, the operator will return to Station 1 and begin another part.

The total cycle time to make a part is still 90 seconds. The average time an operator works on a part is:

90 seconds/1 operator = 90 seconds.

Since the average time per operator of 90 seconds is greater than the maximum cycle time at Station 3 of 40 seconds, the theoretical hourly production is:

3,600 seconds/1 hour • 1 part/90 seconds = 40 parts/hour.

By assuming that the operator will complete a part before starting another part, the utilization of the operator should be 100%. However, the station utilization should be less than 100% and should approximate the station cycle time divided by the total cycle time. For example, the utilization of Station 1 should be:

$$10 \text{ seconds}/90 \text{ seconds} \cdot 100\% = 11\%.$$

Likewise, the utilization of Station 3 should be:

$$40 \text{ seconds}/90 \text{ seconds} \cdot 100\% = 44\%.$$

The MMS is run for 300 seconds to reach equilibrium and for another 3,600 seconds after equilibrium. The model input and simulation results are given in Appendix C. The file name of the model on the disk is *mod1.dat*.

## Two Operators

Let us assume that there are two operators in the line and that the operators can work at any of the four stations. We will now need to define the following rules for the movement of the operators:

- An operator starts at Station 4 and completes a part. If Station 4 is busy, the operator will move to Station 3 and so on until the operator locates a free station with WIP.

- After an operator completes a part at Stations 1,2, or 3, the operator will return to Station 4 and repeat the above rule.

The average time an operator works on a part is :

$$90 \text{ seconds}/2 \text{ operators} = 45 \text{ seconds}.$$

Since the average time per operator of 45 seconds is greater than the maximum cycle time at Station 3 of 40 seconds, the theoretical hourly production is:

$$3,600 \text{ seconds}/1 \text{ hour} \cdot 1 \text{ part}/45 \text{ seconds} = 80 \text{ parts/hour}.$$

The MMS is run for 300 seconds to reach equilibrium and for another 3,600 seconds after equilibrium. The model input and simulation results are given in Appendix C. The file name of the model on the disk is *mod2.dat*.

## Three Operators

Model 3 is similar to Model 2 with the exception of an additional operator, resulting in three operators in the line. The operators can work at any of the four stations. The same operator movement rules apply as for Model 2.

The average time an operator works on a part is:

$$90 \text{ seconds}/3 \text{ operators} = 30 \text{ seconds}.$$

Since the cycle time at Station 3 of 40 seconds is greater than the average time per operator of 30 seconds, the theoretical hourly production is:

$$3,600 \text{ seconds}/1 \text{ hour} \cdot 1 \text{ part}/40 \text{ seconds} = 90 \text{ parts/hour}.$$

Again the MMS is run for 300 seconds to reach equilibrium and another 3,600 seconds after equilibrium. The model input and simulation results are given in Appendix C. The file name of the model on the disk is *mod3.dat*.

## Analysis of Simulation Results

**Production Results.** Figure 28 gives the hourly production as a function of the number of operators and the average production per operator. The results suggest that the maximum production is achieved with three operators. Adding the fourth operator did not increase production. Production dropped with less than three operators. On the other hand, hourly production per operator was the greatest with one or two operators. Production per operator dropped significantly with three operators and even more with four operators. Greater production per operator is achieved with two operators while the greater overall production is achieved with three operators. These results correspond to the theoretical calculations.
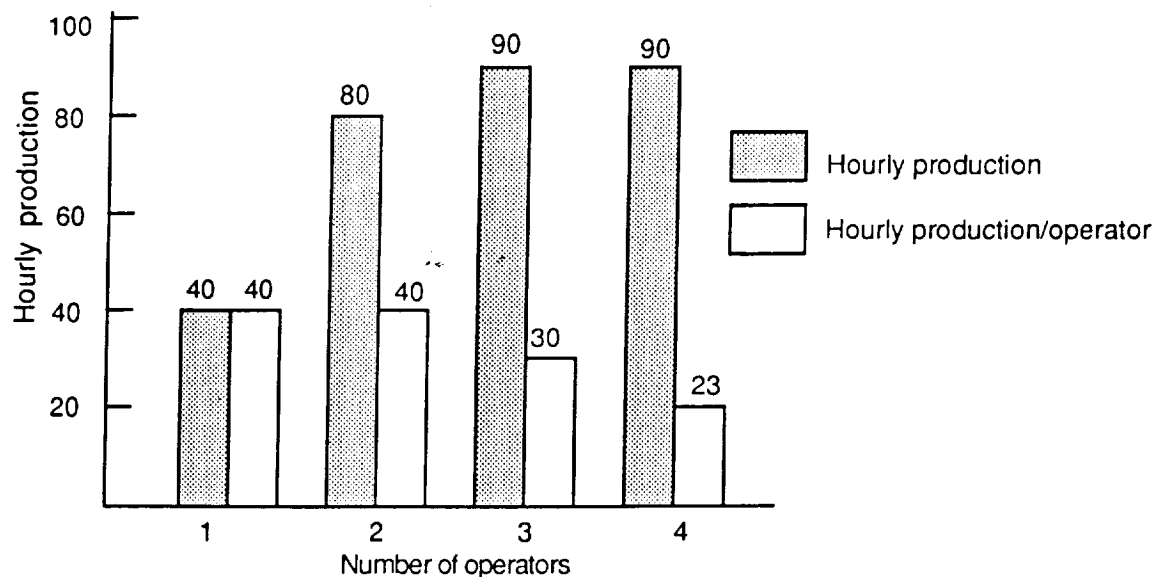


Figure 28. Production statistics

**Work-In-Process Results.** Table I summarizes the average WIP for each model. We can ignore the WIP in front of Station 1 because of the model constraint of always a part in front of Station 1. With four operators the WIP was 105 parts in front of Station 2 and 52 parts in front of Station 3. This WIP would continue to grow by running the model with four operators beyond the 3,900 seconds.

The MMS output statistics with four operators indicate that the maximum queue content and the current queue content were the same for Stations 2 and 3. In other words, the WIP was the greatest at the end of the simulation. Therefore, the WIP should continue to increase with time.

As anticipated there was no WIP in the line with only one operator. The WIP in front of the stations with two operators was less than one part. The WIP with three operators was 52 parts in front of Station 3 and three parts in front of Station 2. Therefore, to minimize WIP, we should select two operators.

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**Operator and Station Utilizations.** Tables II and III give the operator and machine utilizations for each model. With four operators, three of the operators were busy 100% and the fourth operator 50%. Since an operator was assigned to each station, the station utilization was identical to operator utilization.

For one operator, the operator utilization was 100%. The station utilization was 11% for Station 1, 22% for Stations 2 and 4, and 44% for Station 3. These utilizations correspond to the theoretical calculations.

For two operators, the operator utilization was 100%. Also, the station utilization varied from 22% for Station 1, to 44% for Stations 2 and 4, and 89% for Station 3. The 89% utilization for Station 3 is anticipated since Station 3 has the largest cycle time. Furthermore, since the cycle time for Stations 2 and 4 are one-half of Station 3, the station utilization varied accordingly.

For three operators, the operator utilization was 100%. On the other hand, the station utilization varied from 50% for Stations 1 and 4, to 100% for Stations 2 and 3. As expected these utilizations were greater than with two operators.

### Table I. Average WIP

| Number of operators | Machine | | | |
|---|---|---|---|---|
|  | 1 | 2 | 3 | 4 |
| Model 1 | 1 | 1 | 0 | 0 | 0 |
| Model 2 | 2 | 1 | 0 | 1 | 0 |
| Model 3 | 3 | 1 | 3 | 52 | 0 |
| Model 4 | 4 | 1 | 105 | 52 | 0 |

### Table II. Operator utilization

| Number of operators | Operator | | | |
|---|---|---|---|---|
|  | 1 | 2 | 3 | 4 |
| Model 1 | 1 | 100% | | | |
| Model 2 | 2 | 100% | 100% | | |
| Model 3 | 3 | 100% | 100% | 100% | |
| Model 4 | 4 | 100% | 100% | 100% | 50% |

### Table III. Machine utilization

| Number of operators | Machine | | | |
|---|---|---|---|---|
|  | 1 | 2 | 3 | 4 |
| Model 1 | 1 | 11% | 22% | 44% | 22% |
| Model 2 | 2 | 22% | 44% | 88% | 44% |
| Model 3 | 3 | 50% | 100% | 100% | 50% |
| Model 4 | 4 | 100% | 100% | 100% | 50% |

**Adding More Machines.** The bottleneck in production is the 40 second cycle time at Station 3. Therefore, let us add a second machine at Station 3. Also, let us assign four operators to the line.

The total time to make a part is still 90 seconds. The average time an operator works on a part is 90 seconds/4 operators, or 22.5 seconds.

The average cycle time at Station 3 with two machines is 40 seconds/2 machines, or 20 seconds. Therefore, since the average time per operator of 22.5 seconds is greater than the cycle time at Station 3 of 20 seconds, the theoretical hourly production is:

$$3,600 \text{ seconds/1 hour} \cdot 1 \text{ part/22.5 seconds} = 160 \text{ parts/hour.}$$

Note that by adding one machine and with no increase in the number of operators, hourly production was increased from 90 to 160 parts.

The MMS is run for 300 seconds to reach equilibrium and another 3,600 seconds after equilibrium. The model input and simulation results are given in Appendix C. The file name of the model on the disk is *mod4a.dat*.

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# APPENDIX A

## Problems 2 and 3 model inputs and simulation results

MODULAR MANUFACTURING SIMULATOR

Date: 8/20/1996
Model: A:\TSS2.DAT

MODEL INPUT

Stations: 13
Operators: 5

| Station No. Name | | Number of Machines | Cycle Time Distribution |
|---|---|---|---|
| 1 | Sta-1 | 1 | Constant(30.000) |
| 2 | Sta-2 | 1 | Constant(70.000) |
| 3 | Sta-3 | 1 | Constant(60.000) |
| 4 | Sta-4 | 1 | Constant(40.000) |
| 5 | Sta-5 | 1 | Constant(95.000) |
| 6 | Sta-6 | 1 | Constant(5.000) |
| 7 | Sta-7 | 1 | Constant(40.000) |
| 8 | Sta-8 | 1 | Constant(30.000) |
| 9 | Sta-9 | 1 | Constant(5.000) |
| 10 | Sta-10 | 1 | Constant(10.000) |
| 11 | Sta-11 | 1 | Constant(15.000) |
| 12 | Sta-12 | 1 | Constant(20.000) |
| 13 | Sta-13 | 1 | Constant(80.000) |

OPERATOR ASSIGNMENT

| Operator | Name | Type | Station Assignment No. Name |
|---|---|---|---|
| 1 | Operator-1 | PUSH/PULL | |
| 2 | Operator-2 | PUSH/PULL | |
| 3 | Operator-3 | PUSH/PULL | |
| 4 | Operator-4 | PUSH/PULL | |
| 5 | Operator-5 | PUSH/PULL | |

OPERATOR MOVEMENT

| Operator | Station No. Name | | Prio | Eff | Part Limit | Time Limit | Next Station WIP Limit | Override Limit |
|---|---|---|---|---|---|---|---|---|
| Operator-1 | 1 | Sta-1 | 2 | 100 | 0 | 0 | 0 | 0 |
| | 2 | Sta-2 | 1 | 100 | 0 | 0 | 0 | 0 |
| Operator-2 | 3 | Sta-3 | 2 | 100 | 0 | 0 | 0 | 0 |
| | 4 | Sta-4 | 1 | 100 | 0 | 0 | 0 | 0 |
| Operator-3 | 5 | Sta-5 | 2 | 100 | 0 | 0 | 0 | 0 |
| | 6 | Sta-6 | 1 | 100 | 0 | 0 | 0 | 0 |
| Operator-4 | 7 | Sta-7 | 5 | 100 | 0 | 0 | 0 | 0 |
| | 8 | Sta-8 | 4 | 100 | 0 | 0 | 0 | 0 |
| | 9 | Sta-9 | 3 | 100 | 0 | 0 | 0 | 0 |
| | 10 | Sta-10 | 2 | 100 | 0 | 0 | 0 | 0 |
| | 11 | Sta-11 | 1 | 100 | 0 | 0 | 0 | 0 |
| Operator-5 | 12 | Sta-12 | 2 | 100 | 0 | 0 | 0 | 0 |
| | 13 | Sta-13 | 1 | 100 | 0 | 0 | 0 | 0 |

MODULAR MANUFACTURING SIMULATOR

Date: 8/20/1996
Model: A:\TSS2.DAT

SIMULATION RESULTS

Run length: 21600.00
Initialization length: 500.00
RN generator: 1

Production: 216

MACHINE STATISTICS

| Station No. | Name | WIP | Machine | %Busy | Number of Operations |
|---|---|---|---|---|---|
| 1 | Sta-1 | 1 | 1 | 30.00 | 216 |
| 2 | Sta-2 | 0 | 1 | 70.00 | 216 |
| 3 | Sta-3 | 0 | 1 | 60.00 | 216 |
| 4 | Sta-4 | 0 | 1 | 40.00 | 216 |
| 5 | Sta-5 | 0 | 1 | 95.00 | 216 |
| 6 | Sta-6 | 0 | 1 | 5.00 | 216 |
| 7 | Sta-7 | 0 | 1 | 40.00 | 216 |
| 8 | Sta-8 | 0 | 1 | 30.00 | 216 |
| 9 | Sta-9 | 0 | 1 | 5.00 | 216 |
| 10 | Sta-10 | 0 | 1 | 10.00 | 216 |
| 11 | Sta-11 | 0 | 1 | 15.00 | 216 |
| 12 | Sta-12 | 0 | 1 | 20.00 | 216 |
| 13 | Sta-13 | 0 | 1 | 80.00 | 216 |

BUFFER STATISTICS

| Station No. | Name | Avg WIP | Avg Time | In | Out | Now | Min | Max |
|---|---|---|---|---|---|---|---|---|
| 1 | Sta-1 | 1.00 | 100.00 | 216 | 216 | 1 | 1 | 1 |
| 2 | Sta-2 | 0.00 | 0.00 | 216 | 216 | 0 | 0 | 1 |
| 3 | Sta-3 | 0.00 | 0.00 | 216 | 216 | 0 | 0 | 1 |
| 4 | Sta-4 | 0.00 | 0.00 | 216 | 216 | 0 | 0 | 1 |
| 5 | Sta-5 | 0.00 | 0.00 | 216 | 216 | 0 | 0 | 1 |
| 6 | Sta-6 | 0.00 | 0.00 | 216 | 216 | 0 | 0 | 1 |
| 7 | Sta-7 | 0.00 | 0.00 | 216 | 216 | 0 | 0 | 1 |
| 8 | Sta-8 | 0.00 | 0.00 | 216 | 216 | 0 | 0 | 1 |
| 9 | Sta-9 | 0.00 | 0.00 | 216 | 216 | 0 | 0 | 1 |
| 10 | Sta-10 | 0.00 | 0.00 | 216 | 216 | 0 | 0 | 1 |
| 11 | Sta-11 | 0.00 | 0.00 | 216 | 216 | 0 | 0 | 1 |
| 12 | Sta-12 | 0.00 | 0.00 | 216 | 216 | 0 | 0 | 1 |
| 13 | Sta-13 | 0.00 | 0.00 | 216 | 216 | 0 | 0 | 1 |

OPERATOR UTILIZATION(%) BY STATION

| Station No. | Name | Operator 1 | Operator 2 | Operator 3 | Operator 4 | Operator 5 |
|---|---|---|---|---|---|---|
| Idle | | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1 | Sta-1 | 30.00 | | | | |
| 2 | Sta-2 | 70.00 | | | | |
| 3 | Sta-3 | | 60.00 | | | |
| 4 | Sta-4 | | 40.00 | | | |
| 5 | Sta-5 | | | 95.00 | | |
| 6 | Sta-6 | | | 5.00 | | |
| 7 | Sta-7 | | | | 40.00 | |
| 8 | Sta-8 | | | | 30.00 | |
| 9 | Sta-9 | | | | 5.00 | |
| 10 | Sta-10 | | | | 10.00 | |
| 11 | Sta-11 | | | | 15.00 | |
| 12 | Sta-12 | | | | | 20.00 |
| 13 | Sta-13 | | | | | 80.00 |

MODULAR MANUFACTURING SIMULATOR

Date: 8/20/1996
Model: A:\TSS3.DAT

MODEL INPUT

Stations: 14
Operators: 6

| Station |  | Number of | Cycle Time |
| No. | Name | Machines | Distribution |
| --- | --- | --- | --- |
| 1 | Sta-1 | 1 | Constant(200.000) |
| 2 | Sta-2 | 1 | Constant(30.000) |
| 3 | Sta-3 | 1 | Constant(70.000) |
| 4 | Sta-4 | 1 | Constant(60.000) |
| 5 | Sta-5 | 1 | Constant(40.000) |
| 6 | Sta-6 | 1 | Constant(95.000) |
| 7 | Sta-7 | 1 | Constant(5.000) |
| 8 | Sta-8 | 1 | Constant(40.000) |
| 9 | Sta-9 | 1 | Constant(30.000) |
| 10 | Sta-10 | 1 | Constant(5.000) |
| 11 | Sta-11 | 1 | Constant(10.000) |
| 12 | Sta-12 | 1 | Constant(15.000) |
| 13 | Sta-13 | 1 | Constant(20.000) |
| 14 | Sta-14 | 1 | Constant(80.000) |

OPERATOR ASSIGNMENT

| Operator | Name | Type | Station Assignment |  |
|  |  |  | No. | Name |
| --- | --- | --- | --- | --- |
| 1 | Operator-1 | FIXED | 1 | Sta-1 |
| 2 | Operator-2 | RABBIT CHASE |  |  |
| 3 | Operator-3 | RABBIT CHASE |  |  |
| 4 | Operator-4 | RABBIT CHASE |  |  |
| 5 | Operator-5 | RABBIT CHASE |  |  |
| 6 | Operator-6 | RABBIT CHASE |  |  |

OPERATOR MOVEMENT

| Operator | Station |  | Prio | Eff | Part Limit | Time Limit | Next Station WIP Limit | Override Limit |
|  | No. | Name |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Operator-1 | 1 | Sta-1 | 1 | 100 | 0 | 0 | 0 | 0 |
| Operator-2 | 2 | Sta-2 | 1 | 100 | 0 | 0 | 0 | 0 |
|  | 3 | Sta-3 | 2 | 100 | 0 | 0 | 0 | 0 |
| Operator-3 | 4 | Sta-4 | 1 | 100 | 0 | 0 | 0 | 0 |
|  | 5 | Sta-5 | 2 | 100 | 0 | 0 | 0 | 0 |
| Operator-4 | 6 | Sta-6 | 1 | 100 | 0 | 0 | 0 | 0 |
|  | 7 | Sta-7 | 2 | 100 | 0 | 0 | 0 | 0 |
| Operator-5 | 8 | Sta-8 | 1 | 100 | 0 | 0 | 0 | 0 |
|  | 9 | Sta-9 | 2 | 100 | 0 | 0 | 0 | 0 |
|  | 10 | Sta-10 | 3 | 100 | 0 | 0 | 0 | 0 |
|  | 11 | Sta-11 | 4 | 100 | 0 | 0 | 0 | 0 |
|  | 12 | Sta-12 | 5 | 100 | 0 | 0 | 0 | 0 |
| Operator-6 | 13 | Sta-13 | 1 | 100 | 0 | 0 | 0 | 0 |
|  | 14 | Sta-14 | 2 | 100 | 0 |  |  |  |

MODULAR MANUFACTURING SIMULATOR

Date: 8/20/1996
Model: A:\TSS3.DAT

SIMULATION RESULTS

Run length: 21600.00
Initialization length: 500.00
RN generator: 1

Production: 108

MACHINE STATISTICS

| Station No. | Name | WIP | Machine | %Busy | Number of Operations |
|---|---|---|---|---|---|
| 1 | Sta-1 | 1 | 1 | 100.00 | 108 |
| 2 | Sta-2 | 0 | 1 | 15.00 | 108 |
| 3 | Sta-3 | 0 | 1 | 35.00 | 108 |
| 4 | Sta-4 | 0 | 1 | 30.00 | 108 |
| 5 | Sta-5 | 0 | 1 | 20.00 | 108 |
| 6 | Sta-6 | 0 | 1 | 47.50 | 108 |
| 7 | Sta-7 | 0 | 1 | 2.50 | 108 |
| 8 | Sta-8 | 0 | 1 | 20.00 | 108 |
| 9 | Sta-9 | 0 | 1 | 15.00 | 108 |
| 10 | Sta-10 | 0 | 1 | 2.50 | 108 |
| 11 | Sta-11 | 0 | 1 | 5.00 | 108 |
| 12 | Sta-12 | 0 | 1 | 7.50 | 108 |
| 13 | Sta-13 | 0 | 1 | 10.00 | 108 |
| 14 | Sta-14 | 0 | 1 | 40.00 | 108 |

BUFFER STATISTICS

| Station No. | Name | Avg WIP | Avg Time | In | Out | Now | Min | Max |
|---|---|---|---|---|---|---|---|---|
| 1 | Sta-1 | 1.00 | 199.07 | 108 | 108 | 1 | 1 | 1 |
| 2 | Sta-2 | 0.00 | 0.00 | 108 | 108 | 0 | 0 | 1 |
| 3 | Sta-3 | 0.00 | 0.00 | 108 | 108 | 0 | 0 | 1 |
| 4 | Sta-4 | 0.00 | 0.00 | 108 | 108 | 0 | 0 | 1 |
| 5 | Sta-5 | 0.00 | 0.00 | 108 | 108 | 0 | 0 | 1 |
| 6 | Sta-6 | 0.00 | 0.00 | 108 | 108 | 0 | 0 | 1 |
| 7 | Sta-7 | 0.00 | 0.00 | 108 | 108 | 0 | 0 | 1 |
| 8 | Sta-8 | 0.00 | 0.00 | 108 | 108 | 0 | 0 | 1 |
| 9 | Sta-9 | 0.00 | 0.00 | 108 | 108 | 0 | 0 | 1 |
| 10 | Sta-10 | 0.00 | 0.00 | 108 | 108 | 0 | 0 | 1 |
| 11 | Sta-11 | 0.00 | 0.00 | 108 | 108 | 0 | 0 | 1 |
| 12 | Sta-12 | 0.00 | 0.00 | 108 | 108 | 0 | 0 | 1 |
| 13 | Sta-13 | 0.00 | 0.00 | 108 | 108 | 0 | 0 | 1 |
| 14 | Sta-14 | 0.00 | 0.00 | 108 | 108 | 0 | 0 | 1 |

OPERATOR UTILIZATION(%) BY STATION

| Station No. Name | Operator 1 | Operator 2 | Operator 3 | Operator 4 | Operator 5 |
|---|---|---|---|---|---|
| Idle | 0.00 | 50.00 | 50.00 | 50.00 | 50.00 |
| 1   Sta-1 | 100.00 | | | | |
| 2   Sta-2 | | 15.00 | | | |
| 3   Sta-3 | | 35.00 | | | |
| 4   Sta-4 | | | 30.00 | | |
| 5   Sta-5 | | | 20.00 | | |
| 6   Sta-6 | | | | 47.50 | |
| 7   Sta-7 | | | | 2.50 | |
| 8   Sta-8 | | | | | 20.00 |
| 9   Sta-9 | | | | | 15.00 |
| 10  Sta-10 | | | | | 2.50 |
| 11  Sta-11 | | | | | 5.00 |
| 12  Sta-12 | | | | | 7.50 |
| 13  Sta-13 | | | | | |
| 14  Sta-14 | | | | | |

| Station No. Name | Operator 6 |
|---|---|
| Idle | 50.00 |
| Sta-1 | |
| Sta-2 | |
| Sta-3 | |
| Sta-4 | |
| Sta-5 | |
| Sta-6 | |
| Sta-7 | |
| Sta-8 | |
| Sta-9 | |
| 0  Sta-10 | |
| 1  Sta-11 | |
| 2  Sta-12 | |
| 3  Sta-13 | 10.00 |
| 4  Sta-14 | 40.00 |

# APPENDIX B

## Problem 4 model inputs and simulation results

MODULAR MANUFACTURING SIMULATOR

Date: 8/20/1996
Model: A:\OVER1.DAT

MODEL INPUT

Stations: 5
Operators: 3

| Station | | Number of | Cycle Time |
| No. | Name | Machines | Distribution |
|---|---|---|---|
| 1 | Sta-1 | 1 | Constant(30.000) |
| 2 | Sta-2 | 1 | Constant(30.000) |
| 3 | Sta-3 | 1 | Constant(40.000) |
| 4 | Sta-4 | 1 | Constant(30.000) |
| 5 | Sta-5 | 1 | Constant(30.000) |

OPERATOR ASSIGNMENT

| Operator | Name | Type | Station Assignment | |
| | | | No. | Name |
|---|---|---|---|---|
| 1 | Operator-1 | MAX WIP | | |
| 2 | Operator-2 | MAX WIP | | |
| 3 | Operator-3 | MAX WIP | | |

OPERATOR MOVEMENT

| Operator | Station | | Prio | Eff | Part Limit | Time Limit | Next Station WIP Limit | Override Limit |
| | No. | Name | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Operator-1 | 1 | Sta-1 | 1 | 100 | 0 | 0 | 2 | 0 |
| | 2 | Sta-2 | 2 | 100 | 0 | 0 | 2 | 0 |
| | 3 | Sta-3 | 3 | 100 | 0 | 0 | 2 | 0 |
| | 4 | Sta-4 | 4 | 100 | 0 | 0 | 2 | 0 |
| | 5 | Sta-5 | 5 | 100 | 0 | 0 | 2 | 0 |
| Operator-2 | 1 | Sta-1 | 4 | 100 | 0 | 900 | 0 | 0 |
| | 2 | Sta-2 | 5 | 100 | 0 | 900 | 0 | 0 |
| | 3 | Sta-3 | 1 | 100 | 0 | 900 | 0 | 0 |
| | 4 | Sta-4 | 2 | 100 | 0 | 900 | 0 | 0 |
| | 5 | Sta-5 | 3 | 100 | 0 | 900 | 0 | 0 |
| Operator-3 | 1 | Sta-1 | 5 | 100 | 5 | 0 | 0 | 0 |
| | 2 | Sta-2 | 1 | 100 | 5 | 0 | 0 | 0 |
| | 3 | Sta-3 | 2 | 100 | 5 | 0 | 0 | 0 |
| | 4 | Sta-4 | 3 | 100 | 5 | 0 | 0 | 0 |
| | 5 | Sta-5 | 4 | 100 | 5 | 0 | 0 | 0 |

MODULAR MANUFACTURING SIMULATOR

Date: 8/20/1996
Model: A:\OVER1.DAT

SIMULATION RESULTS

Run length: 3600.00
Initialization length: 0.00
RN generator: 1

Production: 52

MACHINE STATISTICS

| Station | | WIP | Machine | %Busy | Number of Operations |
| No. | Name | | | | |
|---|---|---|---|---|---|
| 1 | Sta-1 | 1 | 1 | 46.39 | 55 |
| 2 | Sta-2 | 0 | 1 | 45.56 | 54 |
| 3 | Sta-3 | 0 | 1 | 60.00 | 54 |
| 4 | Sta-4 | 1 | 1 | 44.17 | 53 |
| 5 | Sta-5 | 1 | 1 | 43.33 | 52 |

BUFFER STATISTICS

| Station | | Avg WIP | Avg Time | In | Out | Now | Min | Max |
| No. | Name | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1 | Sta-1 | 0.99 | 65.09 | 55 | 55 | 1 | 1 | 1 |
| 2 | Sta-2 | 0.46 | 30.18 | 55 | 55 | 0 | 0 | 2 |
| 3 | Sta-3 | 2.71 | 180.74 | 54 | 54 | 0 | 0 | 13 |
| 4 | Sta-4 | 2.51 | 170.57 | 54 | 53 | 1 | 0 | 12 |
| 5 | Sta-5 | 3.06 | 211.92 | 53 | 52 | 1 | 0 | 7 |

OPERATOR UTILIZATION(%) BY STATION

| Station | | Operator 1 | Operator 2 | Operator 3 |
| No. | Name | | | |
|---|---|---|---|---|
| Idle | | 7.50 | 37.78 | 15.28 |
| 1 | Sta-1 | 33.89 | 0.00 | 12.50 |
| 2 | Sta-2 | 7.50 | 33.89 | 4.17 |
| 3 | Sta-3 | 7.78 | 16.67 | 35.56 |
| 4 | Sta-4 | 5.00 | 11.67 | 27.50 |
| 5 | Sta-5 | 38.33 | 0.00 | 5.00 |

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MODULAR MANUFACTURING SIMULATOR

Date: 8/20/1996
Model: A:\OVER2.DAT

MODEL INPUT

Stations: 5
Operators: 3

| Station | | Number of | Cycle Time |
|---|---|---|---|
| No. | Name | Machines | Distribution |
| 1 | Sta-1 | 1 | Constant(30.000) |
| 2 | Sta-2 | 1 | Constant(30.000) |
| 3 | Sta-3 | 1 | Constant(40.000) |
| 4 | Sta-4 | 1 | Constant(30.000) |
| 5 | Sta-5 | 1 | Constant(30.000) |

OPERATOR ASSIGNMENT

| Operator | Name | Type | Station Assignment | |
|---|---|---|---|---|
| | | | No. | Name |
| 1 | Operator-1 | MAX WIP | | |
| 2 | Operator-2 | MAX WIP | | |
| 3 | Operator-3 | MAX WIP | | |

OPERATOR MOVEMENT

| Operator | Station | | Prio | Eff | Part Limit | Time Limit | Next Station WIP Limit | Override Limit |
|---|---|---|---|---|---|---|---|---|
| | No. | Name | | | | | | |
| Operator-1 | 1 | Sta-1 | 1 | 100 | 0 | 0 | 2 | 1 |
| | 2 | Sta-2 | 2 | 100 | 0 | 0 | 2 | 1 |
| | 3 | Sta-3 | 3 | 100 | 0 | 0 | 2 | 1 |
| | 4 | Sta-4 | 4 | 100 | 0 | 0 | 2 | 1 |
| | 5 | Sta-5 | 5 | 100 | 0 | 0 | 2 | 1 |
| Operator-2 | 1 | Sta-1 | 4 | 100 | 0 | 900 | 0 | 1 |
| | 2 | Sta-2 | 5 | 100 | 0 | 900 | 0 | 1 |
| | 3 | Sta-3 | 1 | 100 | 0 | 900 | 0 | 1 |
| | 4 | Sta-4 | 2 | 100 | 0 | 900 | 0 | 1 |
| | 5 | Sta-5 | 3 | 100 | 0 | 900 | 0 | 1 |
| Operator-3 | 1 | Sta-1 | 5 | 100 | 5 | 0 | 0 | 1 |
| | 2 | Sta-2 | 1 | 100 | 5 | 0 | 0 | 1 |
| | 3 | Sta-3 | 2 | 100 | 5 | 0 | 0 | 1 |
| | 4 | Sta-4 | 3 | 100 | 5 | 0 | 0 | 1 |
| | 5 | Sta-5 | 4 | 100 | 5 | 0 | 0 | 1 |

MODULAR MANUFACTURING SIMULATOR

Date: 8/20/1996
Model: A:\OVER2.DAT

SIMULATION RESULTS

Run length: 3600.00
Initialization length: 0.00
RN generator: 1

Production: 64

MACHINE STATISTICS

| Station | | WIP | Machine | %Busy | Number of |
|---|---|---|---|---|---|
| No. | Name | | | | Operations |
| 1 | Sta-1 | 1 | 1 | 57.50 | 69 |
| 2 | Sta-2 | 0 | 1 | 57.50 | 69 |
| 3 | Sta-3 | 1 | 1 | 74.72 | 67 |
| 4 | Sta-4 | 1 | 1 | 54.44 | 65 |
| 5 | Sta-5 | 0 | 1 | 53.33 | 64 |

BUFFER STATISTICS

| Station | | Avg WIP | Avg Time | In | Out | Now | Min | Max |
|---|---|---|---|---|---|---|---|---|
| No. | Name | | | | | | | |
| 1 | Sta-1 | 0.97 | 51.47 | 68 | 68 | 1 | 1 | 1 |
| 2 | Sta-2 | 2.23 | 116.23 | 69 | 69 | 0 | 0 | 9 |
| 3 | Sta-3 | 4.82 | 255.15 | 69 | 68 | 1 | 0 | 13 |
| 4 | Sta-4 | 3.34 | 182.12 | 67 | 66 | 1 | 0 | 12 |
| 5 | Sta-5 | 3.74 | 206.92 | 65 | 65 | 0 | 0 | 7 |

OPERATOR UTILIZATION(%) BY STATION

| Station | | Operator 1 | Operator 2 | Operator 3 |
|---|---|---|---|---|
| No. | Name | | | |
| Idle | | 0.00 | 0.83 | 1.67 |
| 1 | Sta-1 | 28.33 | 25.00 | 4.17 |
| 2 | Sta-2 | 22.50 | 26.67 | 8.33 |
| 3 | Sta-3 | 15.83 | 16.67 | 42.22 |
| 4 | Sta-4 | 2.50 | 15.00 | 36.94 |
| 5 | Sta-5 | 30.83 | 15.83 | 6.67 |

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# APPENDIX C

## Case study model inputs and simulation results

MODULAR MANUFACTURING SIMULATOR

Date: 8/20/1996
Model: A:\MOD1.DAT

MODEL INPUT

Stations: 4
Operators: 1

| Station No. Name | Number of Machines | Cycle Time Distribution |
|---|---|---|
| 1  Sta-1 | 1 | Constant(10.000) |
| 2  Sta-2 | 1 | Constant(20.000) |
| 3  Sta-3 | 1 | Constant(40.000) |
| 4  Sta-4 | 1 | Constant(20.000) |

OPERATOR ASSIGNMENT

| Operator | Name | Type | Station Assignment No. Name |
|---|---|---|---|
| 1 | Operator-1 | MAX WIP | |

OPERATOR MOVEMENT

| Operator | Station No. Name | Prio | Eff | Part Limit | Time Limit | Next Station WIP Limit | Override Limit |
|---|---|---|---|---|---|---|---|
| Operator-1 | 1  Sta-1 | 4 | 100 | 0 | 0 | 0 | 0 |
| | 2  Sta-2 | 3 | 100 | 0 | 0 | 0 | 0 |
| | 3  Sta-3 | 2 | 100 | 0 | 0 | 0 | 0 |
| | 4  Sta-4 | 1 | 100 | 0 | 0 | 0 | 0 |

MODULAR MANUFACTURING SIMULATOR

Date: 8/20/1996
Model: A:\MOD1.DAT

SIMULATION RESULTS

Run length: 3600.00
Initialization length: 300.00
RN generator: 1

Production: 40

MACHINE STATISTICS

| Station No. Name | WIP | Machine | %Busy | Number of Operations |
|---|---|---|---|---|
| 1  Sta-1 | 1 | 1 | 11.11 | 40 |
| 2  Sta-2 | 0 | 1 | 22.22 | 40 |
| 3  Sta-3 | 0 | 1 | 44.44 | 40 |
| 4  Sta-4 | 0 | 1 | 22.22 | 40 |

BUFFER STATISTICS

| Station No. Name | Avg WIP | Avg Time | In | Out | Now | Min | Max |
|---|---|---|---|---|---|---|---|
| 1  Sta-1 | 0.99 | 89.25 | 40 | 40 | 1 | 1 | 1 |
| 2  Sta-2 | 0.00 | 0.00 | 40 | 40 | 0 | 0 | 1 |
| 3  Sta-3 | 0.00 | 0.00 | 40 | 40 | 0 | 0 | 1 |
| 4  Sta-4 | 0.00 | 0.00 | 40 | 40 | 0 | 0 | 1 |

OPERATOR UTILIZATION(%) BY STATION

| Station No. Name | Operator 1 |
|---|---|
| Idle | 0.00 |
| 1  Sta-1 | 11.11 |
| 2  Sta-2 | 22.22 |
| 3  Sta-3 | 44.44 |
| 4  Sta-4 | 22.22 |

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MODULAR MANUFACTURING SIMULATOR

Date: 8/20/1996
Model: A:\MOD2.DAT

MODEL INPUT

Stations: 4
Operators: 2

| Station | | Number of | Cycle Time |
|---|---|---|---|
| No. | Name | Machines | Distribution |
| 1 | Sta-1 | 1 | Constant(10.000) |
| 2 | Sta-2 | 1 | Constant(20.000) |
| 3 | Sta-3 | 1 | Constant(40.000) |
| 4 | Sta-4 | 1 | Constant(20.000) |

OPERATOR ASSIGNMENT

| Operator | Name | Type | Station Assignment | |
|---|---|---|---|---|
| | | | No. | Name |
| 1 | Operator-1 | MAX WIP | | |
| 2 | Operator-2 | MAX WIP | | |

OPERATOR MOVEMENT

| Operator | Station | | Prio | Eff | Part Limit | Time Limit | Next Station WIP Limit | Override Limit |
|---|---|---|---|---|---|---|---|---|
| | No. | Name | | | | | | |
| Operator-1 | 1 | Sta-1 | 4 | 100 | 0 | 0 | 0 | 0 |
| | 2 | Sta-2 | 3 | 100 | 0 | 0 | 0 | 0 |
| | 3 | Sta-3 | 2 | 100 | 0 | 0 | 0 | 0 |
| | 4 | Sta-4 | 1 | 100 | 0 | 0 | 0 | 0 |
| Operator-2 | 1 | Sta-1 | 4 | 100 | 0 | 0 | 0 | 0 |
| | 2 | Sta-2 | 3 | 100 | 0 | 0 | 0 | 0 |
| | 3 | Sta-3 | 2 | 100 | 0 | 0 | 0 | 0 |
| | 4 | Sta-4 | 1 | 100 | 0 | 0 | 0 | 0 |

MODULAR MANUFACTURING SIMULATOR

Date: 8/20/1996
Model: A:\MOD2.DAT

SIMULATION RESULTS

Run length: 3600.00
Initialization length: 300.00
RN generator: 1

Production: 80

MACHINE STATISTICS

| Station | | WIP | Machine | %Busy | Number of |
|---|---|---|---|---|---|
| No. | Name | | | | Operations |
| 1 | Sta-1 | 1 | 1 | 22.22 | 80 |
| 2 | Sta-2 | 0 | 1 | 44.44 | 80 |
| 3 | Sta-3 | 1 | 1 | 88.89 | 80 |
| 4 | Sta-4 | 0 | 1 | 44.44 | 80 |

BUFFER STATISTICS

| Station | | Avg WIP | Avg Time | In | Out | Now | Min | Max |
|---|---|---|---|---|---|---|---|---|
| No. | Name | | | | | | | |
| 1 | Sta-1 | 0.99 | 44.62 | 80 | 80 | 1 | 1 | 1 |
| 2 | Sta-2 | 0.00 | 0.00 | 80 | 80 | 0 | 0 | 1 |
| 3 | Sta-3 | 1.00 | 45.00 | 80 | 80 | 1 | 1 | 2 |
| 4 | Sta-4 | 0.00 | 0.00 | 80 | 80 | 0 | 0 | 1 |

OPERATOR UTILIZATION(%) BY STATION

| Station | | Operator 1 | Operator 2 |
|---|---|---|---|
| No. | Name | | |
| Idle | | 0.00 | 0.00 |
| 1 | Sta-1 | 11.11 | 11.11 |
| 2 | Sta-2 | 22.22 | 22.22 |
| 3 | Sta-3 | 44.44 | 44.44 |
| 4 | Sta-4 | 22.22 | 22.22 |

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MODULAR MANUFACTURING SIMULATOR

Date: 8/20/1996
Model: A:\MOD3.DAT

MODEL INPUT

Stations: 4
Operators: 3

| Station No. | Name | Number of Machines | Cycle Time Distribution |
|---|---|---|---|
| 1 | Sta-1 | 1 | Constant(10.000) |
| 2 | Sta-2 | 1 | Constant(20.000) |
| 3 | Sta-3 | 1 | Constant(40.000) |
| 4 | Sta-4 | 1 | Constant(20.000) |

OPERATOR ASSIGNMENT

| Operator | Name | Type | Station Assignment No. Name |
|---|---|---|---|
| 1 | Operator-1 | MAX WIP | |
| 2 | Operator-2 | MAX WIP | |
| 3 | Operator-3 | MAX WIP | |

OPERATOR MOVEMENT

| Operator | Station No. | Name | Prio | Eff | Part Limit | Time Limit | Next Station WIP Limit | Override Limit |
|---|---|---|---|---|---|---|---|---|
| Operator-1 | 1 | Sta-1 | 4 | 100 | 0 | 0 | 0 | 0 |
| | 2 | Sta-2 | 3 | 100 | 0 | 0 | 0 | 0 |
| | 3 | Sta-3 | 2 | 100 | 0 | 0 | 0 | 0 |
| | 4 | Sta-4 | 1 | 100 | 0 | 0 | 0 | 0 |
| Operator-2 | 1 | Sta-1 | 4 | 100 | 0 | 0 | 0 | 0 |
| | 2 | Sta-2 | 3 | 100 | 0 | 0 | 0 | 0 |
| | 3 | Sta-3 | 2 | 100 | 0 | 0 | 0 | 0 |
| | 4 | Sta-4 | 1 | 100 | 0 | 0 | 0 | 0 |
| Operator-3 | 1 | Sta-1 | 4 | 100 | 0 | 0 | 0 | 0 |
| | 2 | Sta-2 | 3 | 100 | 0 | 0 | 0 | 0 |
| | 3 | Sta-3 | 2 | 100 | 0 | 0 | 0 | 0 |
| | 4 | Sta-4 | 1 | 100 | 0 | 0 | 0 | 0 |

MODULAR MANUFACTURING SIMULATOR

Date: 8/20/1996
Model: A:\MOD3.DAT

SIMULATION RESULTS

Run length: 3600.00
Initialization length: 300.00
RN generator: 1

Production: 90

MACHINE STATISTICS

| Station No. | Name | WIP | Machine | %Busy | Number of Operations |
|---|---|---|---|---|---|
| 1 | Sta-1 | 1 | 1 | 50.00 | 180 |
| 2 | Sta-2 | 3 | 1 | 100.00 | 180 |
| 3 | Sta-3 | 97 | 1 | 100.00 | 90 |
| 4 | Sta-4 | 0 | 1 | 50.00 | 90 |

BUFFER STATISTICS

| Station No. | Name | Avg WIP | Avg Time | In | Out | Now | Min | Max |
|---|---|---|---|---|---|---|---|---|
| 1 | Sta-1 | 1.00 | 20.00 | 180 | 180 | 1 | 1 | 1 |
| 2 | Sta-2 | 2.75 | 55.00 | 180 | 180 | 3 | 2 | 3 |
| 3 | Sta-3 | 51.48 | 2059.22 | 180 | 90 | 97 | 6 | 97 |
| 4 | Sta-4 | 0.00 | 0.00 | 90 | 90 | 0 | 0 | 1 |

OPERATOR UTILIZATION(%) BY STATION

| Station No. | Name | Operator 1 | Operator 2 | Operator 3 |
|---|---|---|---|---|
| Idle | | 0.00 | 0.00 | 0.00 |
| 1 | Sta-1 | 50.00 | 0.00 | 0.00 |
| 2 | Sta-2 | 0.00 | 0.00 | 100.00 |
| 3 | Sta-3 | 0.00 | 100.00 | 0.00 |
| 4 | Sta-4 | 50.00 | 0.00 | 0.00 |

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MODULAR MANUFACTURING SIMULATOR

Date: 8/20/1996
Model: A:\MOD4.DAT

MODEL INPUT

Stations: 4
Operators: 4

| Station No. Name | Number of Machines | Cycle Time Distribution |
|---|---|---|
| 1  Sta-1 | 1 | Constant(10.000) |
| 2  Sta-2 | 1 | Constant(20.000) |
| 3  Sta-3 | 1 | Constant(40.000) |
| 4  Sta-4 | 1 | Constant(20.000) |

OPERATOR ASSIGNMENT

| Operator | Name | Type | Station Assignment No. Name |
|---|---|---|---|
| 1 | Operator-1 | FIXED | 1  Sta-1 |
| 2 | Operator-2 | FIXED | 2  Sta-2 |
| 3 | Operator-3 | FIXED | 3  Sta-3 |
| 4 | Operator-4 | FIXED | 4  Sta-4 |

OPERATOR MOVEMENT

| Operator | Station No. Name | Prio | Eff | Part Limit | Time Limit | Next Station WIP Limit | Override Limit |
|---|---|---|---|---|---|---|---|
| Operator-1 | 1  Sta-1 | 1 | 100 | 0 | 0 | 0 | 0 |
| Operator-2 | 2  Sta-2 | 1 | 100 | 0 | 0 | 0 | 0 |
| Operator-3 | 3  Sta-3 | 1 | 100 | 0 | 0 | 0 | 0 |
| Operator-4 | 4  Sta-4 | 1 | 100 | 0 | 0 | 0 | 0 |

MODULAR MANUFACTURING SIMULATOR

Date: 8/20/1996
Model: A:\MOD4.DAT

SIMULATION RESULTS

Run length: 3600.00
Initialization length: 500.00
RN generator: 1

Production: 90

MACHINE STATISTICS

| Station No. Name | WIP | Machine | %Busy | Number of Operations |
|---|---|---|---|---|
| 1  Sta-1 | 1 | 1 | 100.00 | 360 |
| 2  Sta-2 | 205 | 1 | 100.00 | 180 |
| 3  Sta-3 | 102 | 1 | 100.00 | 90 |
| 4  Sta-4 | 0 | 1 | 50.00 | 90 |

BUFFER STATISTICS

| Station No. Name | Avg WIP | Avg Time | In | Out | Now | Min | Max |
|---|---|---|---|---|---|---|---|
| 1  Sta-1 | 1.00 | 10.00 | 360 | 360 | 1 | 1 | 1 |
| 2  Sta-2 | 114.50 | 2290.00 | 360 | 180 | 205 | 24 | 205 |
| 3  Sta-3 | 56.47 | 2258.67 | 180 | 90 | 102 | 11 | 102 |
| 4  Sta-4 | 0.00 | 0.00 | 90 | 90 | 0 | 0 | 1 |

OPERATOR UTILIZATION(%) BY STATION

| Station No. Name | Operator 1 | Operator 2 | Operator 3 | Operator 4 |
|---|---|---|---|---|
| Idle | 0.00 | 0.00 | 0.00 | 50.00 |
| 1  Sta-1 | 100.00 | | | |
| 2  Sta-2 | | 100.00 | | |
| 3  Sta-3 | | | 100.00 | |
| 4  Sta-4 | | | | 50.00 |

MODULAR MANUFACTURING SIMULATOR

Date: 8/20/1996
Model: A:\MOD4A.DAT

MODEL INPUT

Stations: 4
Operators: 4

| Station No. | Name | Number of Machines | Cycle Time Distribution |
|---|---|---|---|
| 1 | Sta-1 | 1 | Constant(10.000) |
| 2 | Sta-2 | 1 | Constant(20.000) |
| 3 | Sta-3 | 2 | Constant(40.000) |
| 4 | Sta-4 | 1 | Constant(20.000) |

OPERATOR ASSIGNMENT

| Operator | Name | Type | Station Assignment No. | Name |
|---|---|---|---|---|
| 1 | Operator-1 | MAX WIP | | |
| 2 | Operator-2 | MAX WIP | | |
| 3 | Operator-3 | FIXED | 3 | Sta-3 |
| 4 | Operator-4 | MAX WIP | | |

OPERATOR MOVEMENT

| Operator | Station No. | Name | Prio | Eff | Part Limit | Time Limit | Next Station WIP Limit | Override Limit |
|---|---|---|---|---|---|---|---|---|
| Operator-1 | 1 | Sta-1 | 1 | 100 | 0 | 0 | 0 | 0 |
| | 2 | Sta-2 | 2 | 100 | 0 | 0 | 0 | 0 |
| | 3 | Sta-3 | 3 | 100 | 0 | 0 | 0 | 0 |
| | 4 | Sta-4 | 4 | 100 | 0 | 0 | 0 | 0 |
| Operator-2 | 1 | Sta-1 | 4 | 100 | 0 | 0 | 0 | 0 |
| | 2 | Sta-2 | 1 | 100 | 0 | 0 | 0 | 0 |
| | 3 | Sta-3 | 2 | 100 | 0 | 0 | 0 | 0 |
| | 4 | Sta-4 | 3 | 100 | 0 | 0 | 0 | 0 |
| Operator-3 | 3 | Sta-3 | 1 | 100 | 0 | 0 | 0 | 0 |
| Operator-4 | 1 | Sta-1 | 2 | 100 | 0 | 0 | 0 | 0 |
| | 2 | Sta-2 | 3 | 100 | 0 | 0 | 0 | 0 |
| | 3 | Sta-3 | 4 | 100 | 0 | 0 | 0 | 0 |
| | 4 | Sta-4 | 1 | 100 | 0 | 0 | 0 | 0 |

MODULAR MANUFACTURING SIMULATOR

Date: 8/20/1996
Model: A:\MOD4A.DAT

SIMULATION RESULTS

Run length: 3600.00
Initialization length: 300.00
RN generator: 1

Production: 160

MACHINE STATISTICS

| Station No. | Name | WIP | Machine | %Busy | Number of Operations |
|---|---|---|---|---|---|
| 1 | Sta-1 | 1 | 1 | 44.72 | 161 |
| 2 | Sta-2 | 1 | 1 | 88.61 | 160 |
| 3 | Sta-3 | 1 | 1 | 100.00 | 90 |
| | | | 2 | 77.78 | 70 |
| 4 | Sta-4 | 0 | 1 | 88.89 | 160 |

BUFFER STATISTICS

| Station No. | Name | Avg WIP | Avg Time | In | Out | Now | Min | Max |
|---|---|---|---|---|---|---|---|---|
| 1 | Sta-1 | 0.99 | 22.05 | 161 | 161 | 1 | 1 | 1 |
| 2 | Sta-2 | 1.40 | 31.56 | 161 | 160 | 1 | 0 | 4 |
| 3 | Sta-3 | 0.48 | 10.75 | 160 | 160 | 1 | 0 | 2 |
| 4 | Sta-4 | 0.17 | 3.75 | 160 | 160 | 0 | 0 | 1 |

OPERATOR UTILIZATION(%) BY STATION

| Station No. | Name | Operator 1 | Operator 2 | Operator 3 | Operator 4 |
|---|---|---|---|---|---|
| Idle | | 0.00 | 0.00 | 0.00 | 0.00 |
| 1 | Sta-1 | 11.11 | 11.39 | | 22.22 |
| 2 | Sta-2 | 87.78 | 0.83 | | 0.00 |
| 3 | Sta-3 | 1.11 | 76.67 | 100.00 | 0.00 |
| 4 | Sta-4 | 0.00 | 11.11 | | 77.78 |

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